Linee di ricerca RSN4 – Fisica Fondamentale (Gravitazione)

Giornate INAF del Raggruppamento Scientifico Nazionale 4: Astrofisica Relativistica e Particelle

Roberto Peron, INAF-IAPS, roberto.peron@inaf.it

INAF – Osservatorio Astronomico Capodimonte

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Disclaimer and thanks

- **Will not talk** about:
  - GW (well, not exactly…)
  - Cosmology (see RSN1)
- Had to be / tried to be **synthetic** (but didn't succeed)
- Tried to be **comprehensive** but could have overlooked something (in case, please raise your hand!)

For the material, **thanks** to:

F. Santoli, D.M. Lucchesi, M. Negusini, M. Crosta, A. Possenti, M. Burgay, E. Liuzzo, T. Belloni, A. Bazzano, P. Ubertini, A. De Rosa, M. Feroci, L. Piro, A. Stamerra

Summary of presented activities

From ‘local’ to ‘global’ scales:

- Laboratory tests of gravitational theories
- VLBI (geodetic and metrology)
- Near-Earth tests of gravitational theories and geodesy
- Solar System tests of gravitational theories
- Relativistic metrology, gravitational astronomy
- Compact objects (tests of gravitational theories, PTA, BH mass and spin, Kerr metric, gravitomagnetism, EOS, …)
- Multi-messenger astronomy (speed of gravitation, Lorentz Invariance, EOS, …)
- …

Found (much) more than expected!

Gravitation @IAPS
A common history of experience and expertise

Origins, 70s

The Experimental Gravitation Group starts its activity in the Laboratorio Plasma Spazio (LPS) of CNR, under the leadership of **Guido Pizzella** and **Edoardo Amaldi**.

Resonant antenna

At Frascati is installed a cryogenic resonant bar antenna (300 kg) for the **detection of gravitational waves.** The mechanical signal of the antenna is read out by an **electromechanical transductor** initially piezoelectric and subsequently capacitive, amplified by **low-noise devices** and analyzed with **algorithms for the extraction of weak signals inside noise**.

80s

Headed by **Franco Fuligni** and **Valerio Iafolla**, it starts the development of an **accelerometer for space use**, based on the experience gathered in the search for gravitational waves.

2000s

At the beginning of 2000s, after the pioneering work of **Ignazio Ciufolini**, **David Lucchesi** carries in the Group the activity of **General Relativity measurements with laser-ranges geodynamics satellites**.

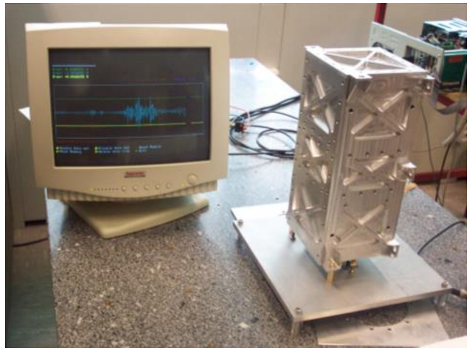
2003

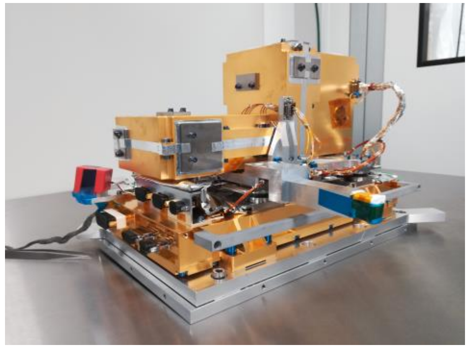
The Group developed, with industry collaboration, the **ISA accelerometer** for ESA **BepiColombo** mission and directly manages its operations since **launch in 2018.**

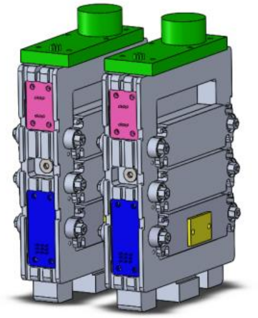
2008

From the Group stem a spin-off: **AGI Assist in Gravitation and Instrumentation**.

Accelerometers development







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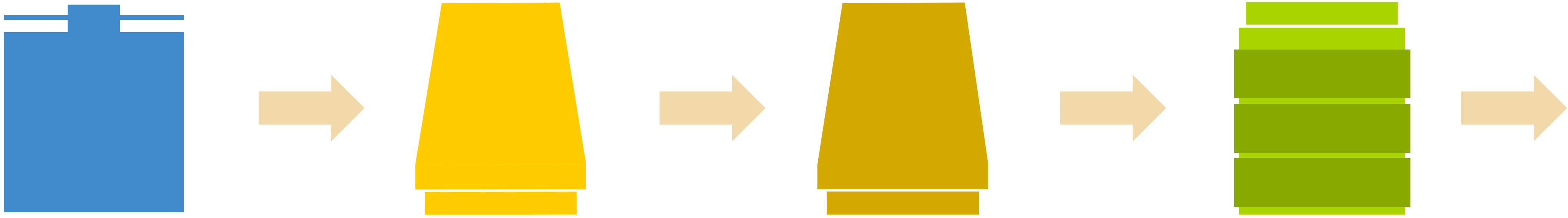
2003 | 2010 | 2016 | 2022 | 2024



New concept

Prototipi ISA

Conceived and built by the Group @ CNR-IFSI

ISA FM

Bandwidth $3*10^{-5}$ – 10^{-1} Hz
Accuracy 10^{-8} m/s^2

HAA FM

Radhard
Bandwidth 10^{-4} – 10^{-1} Hz
Accuracy 10^{-8} m/s^2

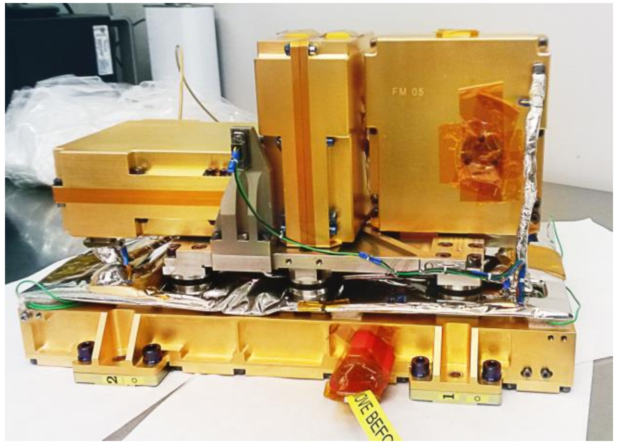
AGES DM

Bandwidth $3*10^{-5}$ – 10^{-3} Hz
Accuracy 10^{-10} m/s^2

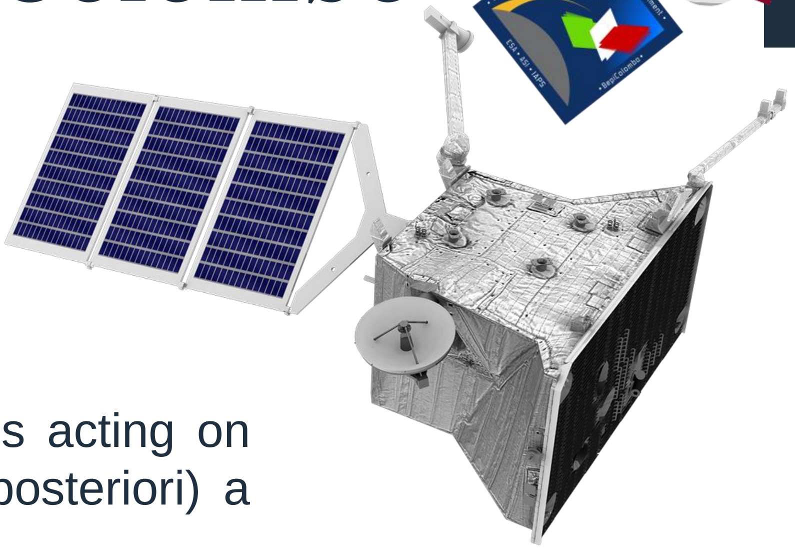
G4S

?

Italian Spring Accelerometer – BepiColombo



ISA - Italian Spring Accelerometer, is the high sensitivity accelerometer on board the Mercury Planetary Orbiter (MPO) of ESA BepiColombo mission.



By measuring the non-gravitational accelerations acting on the spacecraft, it will allow the MPO to be (a posteriori) a ‘test mass’ along a spacetime geodesic.

In the context of Radio Science experiments, ISA will contribute to the study of **Mercury** gravitational field and rotation state, and to test **General Relativity (PPN parameters)** with never achieved before (especially for γ parameter).

ISA is the **first** high-sensitivity accelerometer to have done measurements on board an interplanetary spacecraft.

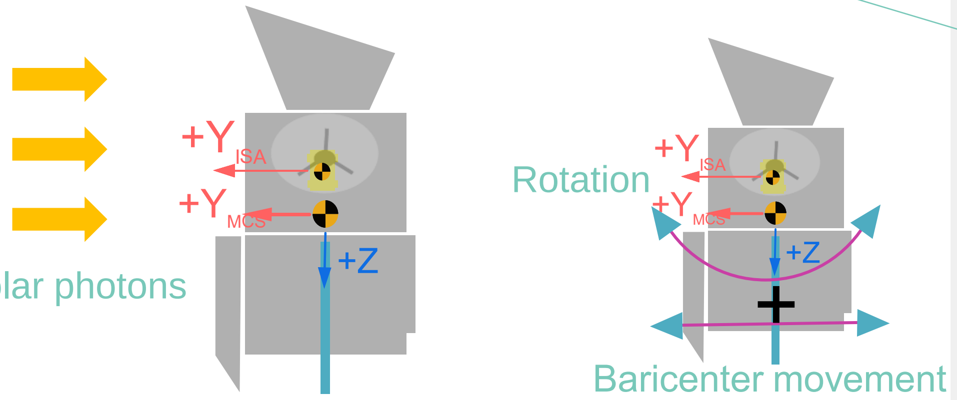
It performance is at the level of the best accelerometers for space use.

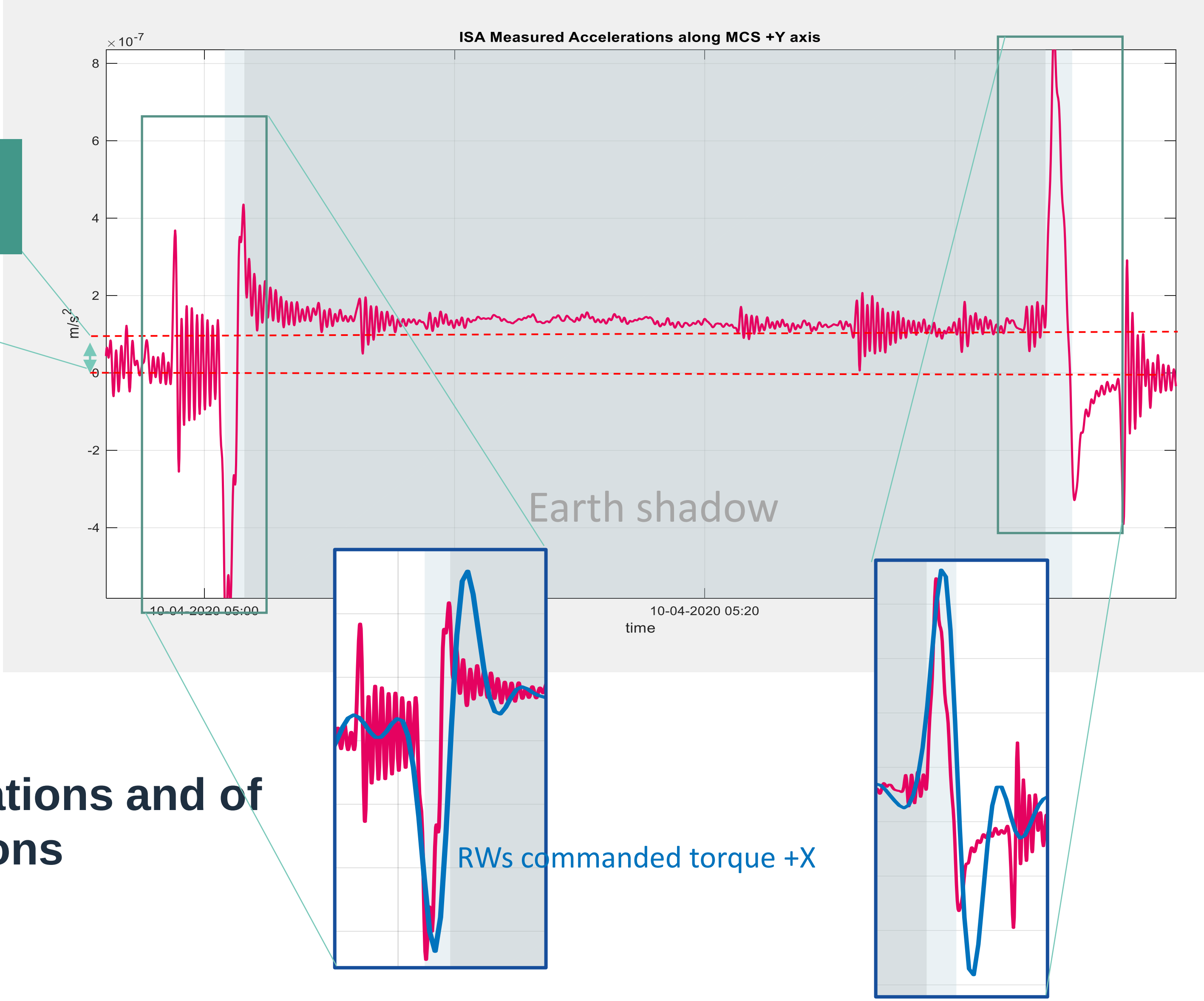
Italian Spring Accelerometer – BepiColombo

Earth flyby

1. Solar radiation pressure measurement

$1.21\ 10^{-7}\ m/s^2$

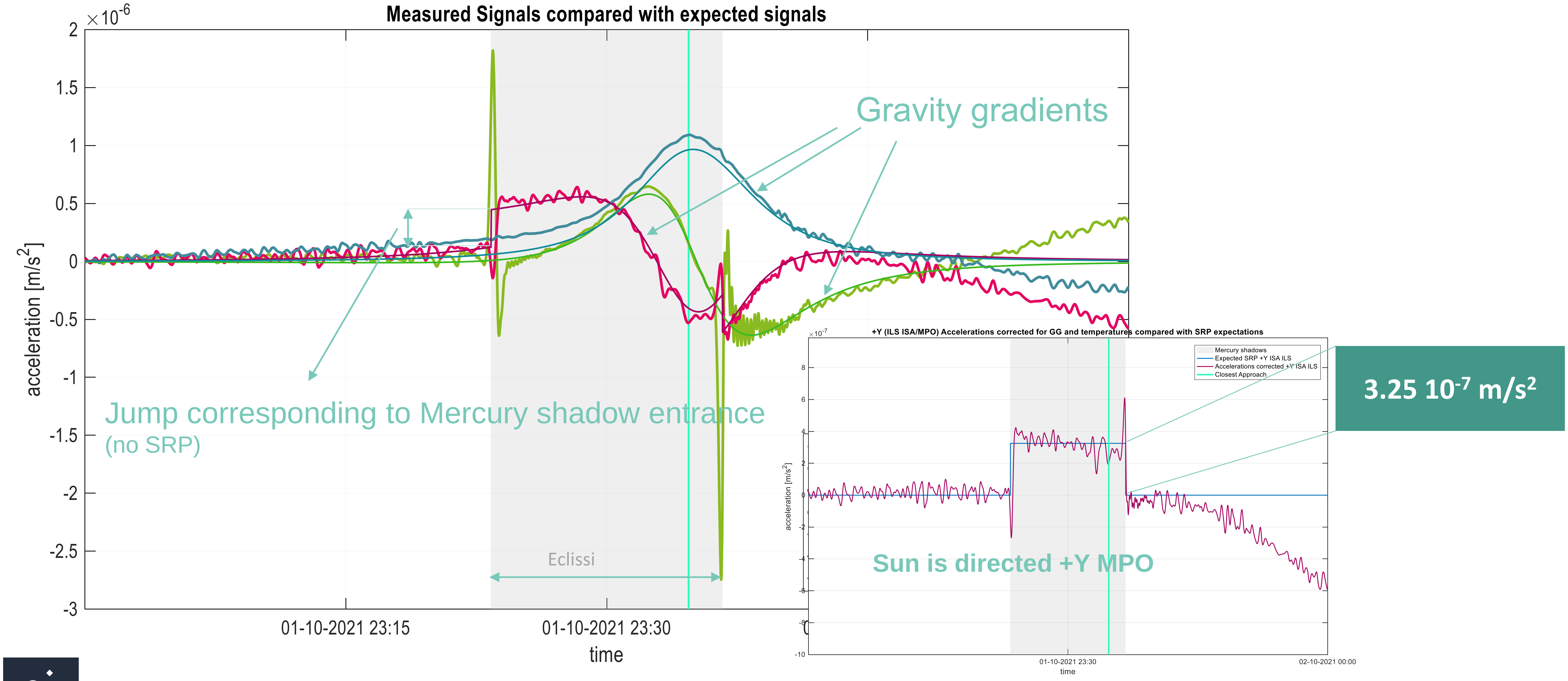




2. Observation of the appendices oscillations and of the attitude control system compensations

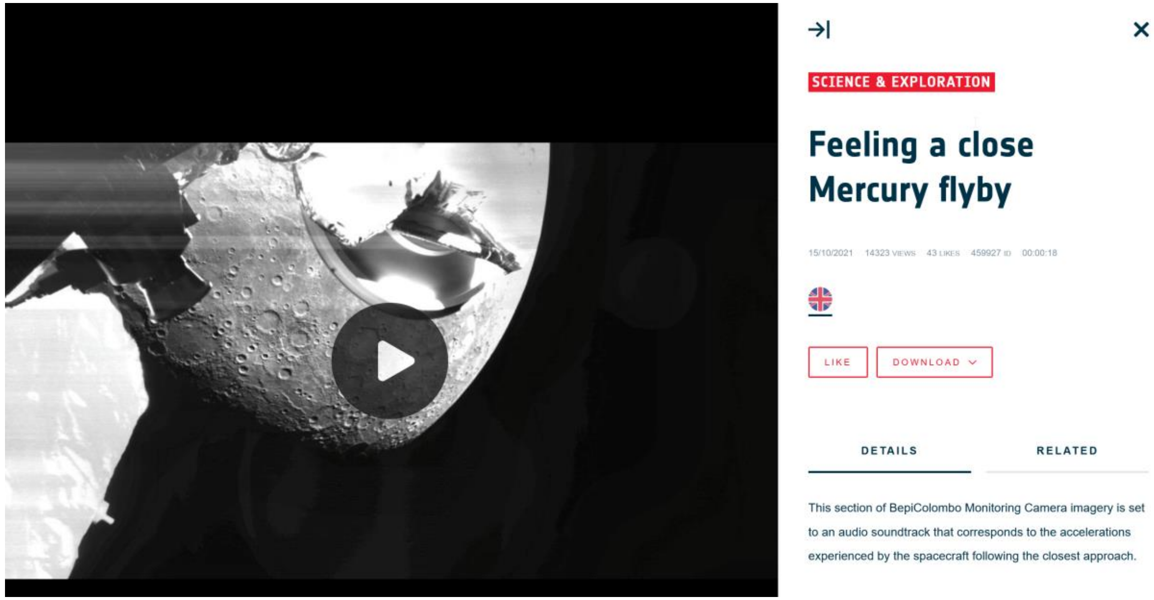
Italian Spring Accelerometer – BepiColombo

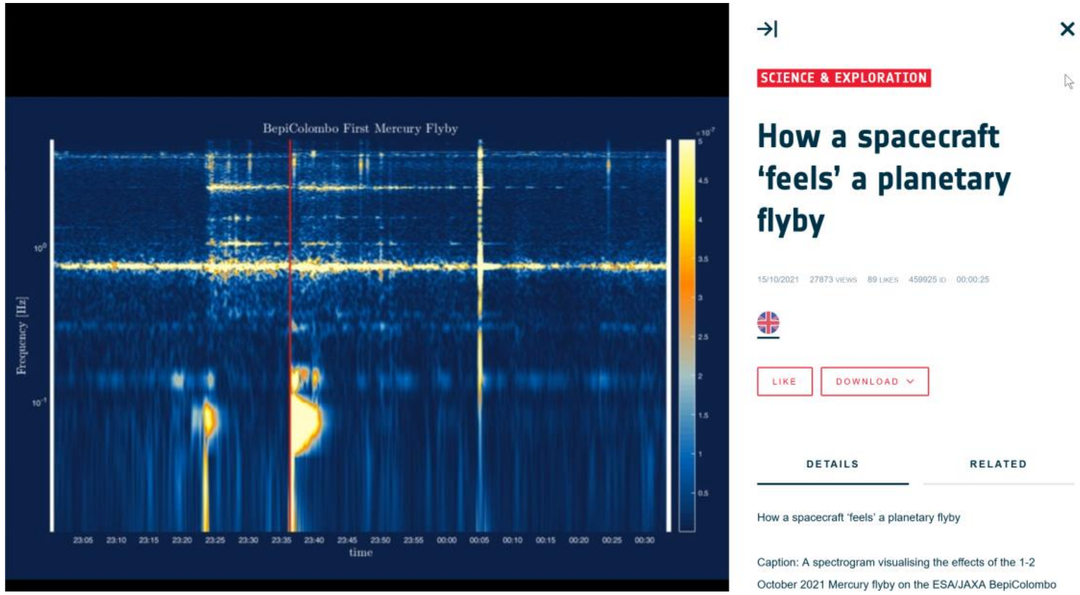
Mercury flyby #1



Italian Spring Accelerometer – BepiColombo

Mercury flyby #2



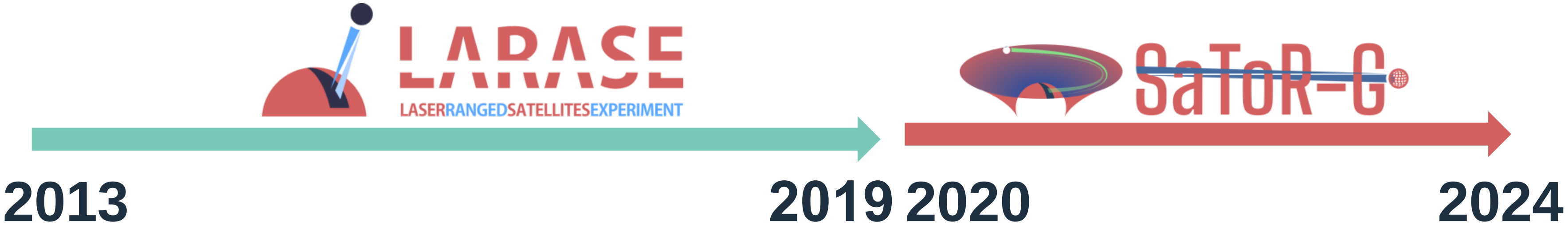


LARASE + SaToR-G

Satellite **T**ests **o**f **R**elativistic **G**ravity (**SaToR-G**) is a fundamental physics experiment funded by the **National Scientific Committee 2 (CSN2)** of the Italian **National Institute for Nuclear Physics (INFN)**

The experiment aims at testing gravitation beyond the predictions of **Einstein's Theory** of **General Relativity (GR)** in its **weak-field and slow-motion (WFSM)** limit, searching for effects foreseen by **alternative theories of gravitation (ATG)** and possibly connected with **''new physics''**

SaToR-G builds on the improved dynamical model of the two **LAGEOS** and **LARES** satellites achieved within the previous project **LARASE (LAser RAnged Satellites Experiment)**, still funded by **CSN2-INFN**



The improvements concern the modelling of both gravitational and **non-gravitational perturbations**

LARASE + SaToR-G
Modelling the satellite dynamics

An important aspect of our activities lies in continuously improving the dynamic model of the orbits of satellites, in particular the models related to:

1. Non-Gravitational perturbations
2. Gravitational perturbations

This activity of development of perturbative models, in particular for non-gravitational forces, constituted one of the major results of **LARASE**, beyond the significant measurements obtained in the field of fundamental physics, and still constitutes a salient activity that characterises the current **SaToR-G** experiment

The **LARASE** results:

1. Reconstruction of the internal structure of the two **LAGEOS** satellites and of **LARES**: mass and moments of inertia
2. Spin model for the three satellites: general and averaged
3. Thermal model of the three satellites: general and averaged
4. Neutral drag model for **LARES**

M. Visco, D. Lucchesi, *Review and critical analysis of mass and moments of inertia of the LAGEOS and LAGEOS II satellites for the LARASE program*. Adv. in Space Res. 57, 044034 doi:10.1016/j.asr.2016.02.006, 2016
M. Visco, D. Lucchesi, *Comprehensive model for the spin evolution of the LAGEOS and LARES satellites*. Phys. Rev. D 98, 044034 doi:10.1103/PhysRevD.98.044034, 2018
Pardini, C.; Anselmo, L.; Lucchesi, D.M.; Peron, R. *On the secular decay of the LARES semi-major axis*. Acta Astronautica 2017, 140, 469–477. doi:10.1016/j.actaastro.2017.09.012

LARASE + SaToR-G
Modelling the satellite dynamics

LArase **S**atellites **S**pin m**O**del **S**olutions (**LASSOS**)

LArase **T**hermal m**O**del **S**olutions **(LATOS)**

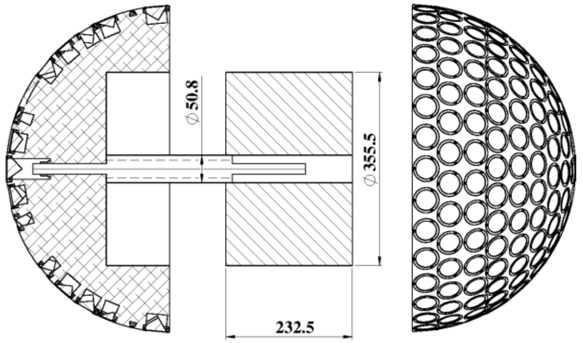


Table 1
Materials used for the construction of the two LAGEOS satellites (Cogo, 1988) and their nominal densities.

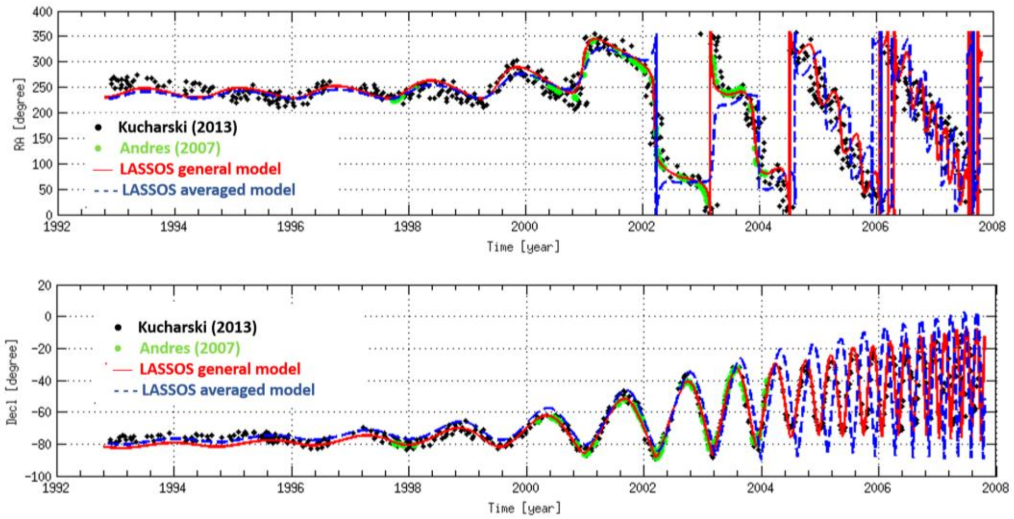
Satellite	Material density ρ_n (kg/m^3)		
	Hemispheres	Core	Stud
LAGEOS	AA6061 2700[a]	QQ-B-626 COMP.11 8440[a]	Cu-Be 8230[b]
LAGEOS II	AlMgSiCu UNI 6170 2740[c]	PCuZn39Pb2 UNI 5706 8280[c]	Cu-Be QQ-C-172 8250[c]

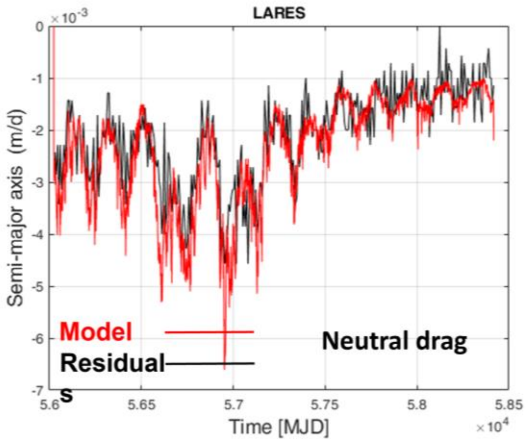
[a] ASM International Handbook Committee (1990).
[b] Baucchio (1993).
[c] It is the value calculated in Cogo (1988) starting from the measured averaged composition.

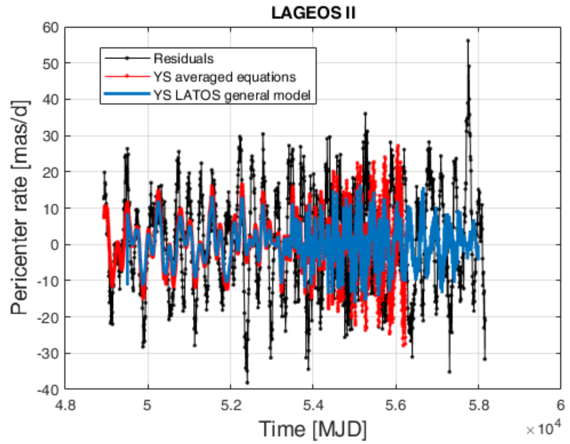
Table 1. Principal moments of inertia of LAGEOS, LAGEOS II and LARES in their flight arrangement.

Satellite	Moments of Inertia (kg m^2)		
	I_{zz}	I_{xx}	I_{yy}
LAGEOS	11.42 ± 0.03	10.96 ± 0.03	10.96 ± 0.03
LAGEOS II	11.45 ± 0.03	11.00 ± 0.03	11.00 ± 0.03
LARES	4.77 ± 0.03	4.77 ± 0.03	4.77 ± 0.03

Spin Orientation: α, δ







LARASE + SaToR-G

Main science results

1. A precise and accurate measurement of the total relativistic advancement (ε) of the pericenter of **LAGEOS II** (mainly produced by the Earth's **Gravitoelectric** field), with consequent constraints on alternative theories of gravitation

$$\boldsymbol{\varepsilon_{meas} - 1 = (-0.12 \pm 2.10) \cdot 10^{-3} \pm 2.5 \cdot 10^{-2}} \qquad \begin{bmatrix} \varepsilon_{GR} = 1 \\ \varepsilon_{New} = 0 \end{bmatrix}$$

2. A precise and accurate measurement of the precession (μ) of the node of the orbits of the two **LAGEOS** and of the **LARES** produced by the Earth's **Gravitomagnetic** field

$$\boldsymbol{\mu_{meas} - 1 = 1.5 \times 10^{-3} \pm 7.4 \times 10^{-3} \pm 16 \times 10^{-3}} \qquad \begin{bmatrix} \mu_{GR} = 1 \\ \mu_{New} = 0 \end{bmatrix}$$

From the first measurement the following constraints were derived:

1. On the combination of the **PPN** parameters β and γ of **General Relativity**
2. On the intensity α of a **Yukawa-like** potential on a scale λ of about 1 Earth radius
3. On **non-symmetric** theories of gravitation
4. On **torsional** theories of gravitation

LARASE + SaToR-G

Main science results – Constraints

$$\varepsilon_{meas} - 1 = (-0.12 \pm 2.10) \cdot 10^{-3} \pm 2.5 \cdot 10^{-2}$$

TABLE XVIII. Summary of the results obtained in the present work; together with the measurement error budget, the constraints on fundamental physics are listed and compared with the literature.

	Parameter	Values and uncertainties (this study)	Uncertainties (literature)	Remarks
	$\epsilon_\omega - 1$	$-1.2 \times 10^{-4} \pm 2.10 \times 10^{-3} \pm 2.54 \times 10^{-2}$	...	Error budget of the perigee precession measurement in the field of the Earth
PPN →	$\frac{\lvert 2+2\gamma-\beta \rvert}{3} - 1$	$-1.2 \times 10^{-4} \pm 2.10 \times 10^{-3} \pm 2.54 \times 10^{-2}$	$\pm(1.0 \times 10^{-3}) \pm (2 \times 10^{-2})$[a]	Constraint on the combination of PPN parameters
Yukawa →	$\lvert\alpha\rvert$	$\lesssim \lvert 0.5 \pm 8.0 \pm 101 \rvert \times 10^{-12}$	$\pm 1 \times 10^{-8}$[b]	Constraint on a possible (Yukawa-like) NLRI
ATGs →	$\mathcal{C}_{\oplus \mathrm{LAGEOSII}}$	$\leq (0.003\ \mathrm{km})^4 \pm (0.036\ \mathrm{km})^4 \pm (0.092\ \mathrm{km})^4$	$\pm(0.16\ \mathrm{km})^4$[c]; $\pm(0.087\ \mathrm{km})^4$[d]	Constraint on a possible NSGT
	$\lvert 2t_2 + t_3 \rvert$	$\lesssim 3.5 \times 10^{-4} \pm 6.2 \times 10^{-3} \pm 7.49 \times 10^{-2}$	3×10^{-3}[e]	Constraint on torsion

[a] From the preliminary estimate of the systematic errors of [166] for the perihelion precession of Mercury.
[b] From [167] with Lunar-LAGEOS *GM* measurements.
[c] From [5] and based on a partial estimate for the systematic errors.
[d] From [7] and based on the analysis of the systematic errors only.
[e] From [168] with no estimate for the systematic errors.

D.M. Lucchesi, R. Peron, *Accurate measurement in the Field of the Earth of he General-Relativistic Precession of the LAGEOS II Pericenter and New Constraints on Non-Newtonian Gravity*, Phys. Rev. Lett. 105, 231103, 2010

D.M. Lucchesi, R. Peron, *LAGEOS II pericenter general relativistic precession (1993-2005): Error budget and constraints in gravitational physics*. Phys. Rev. D 89, 082002, 2014

LARASE + SaToR-G

Main science results – Yukawa-like long-range force

$$|\boldsymbol{\alpha}| \cong \left|(\mathbf{0.5} \pm \mathbf{8}) \cdot \mathbf{10^{-12}} \pm \mathbf{101} \cdot \mathbf{10^{-12}}\right|$$

$$V_{yuk} = -\alpha \frac{G_\infty M_1}{r} e^{-r/\lambda}$$

$$\alpha = \frac{1}{G_\infty}\left(\frac{K_1}{M_1} \cdot \frac{K_2}{M_2}\right)$$

$$\lambda = \frac{h}{\mu c}$$

M_1 = Mass of the primary source;

M_2 = Mass of the secondary source;

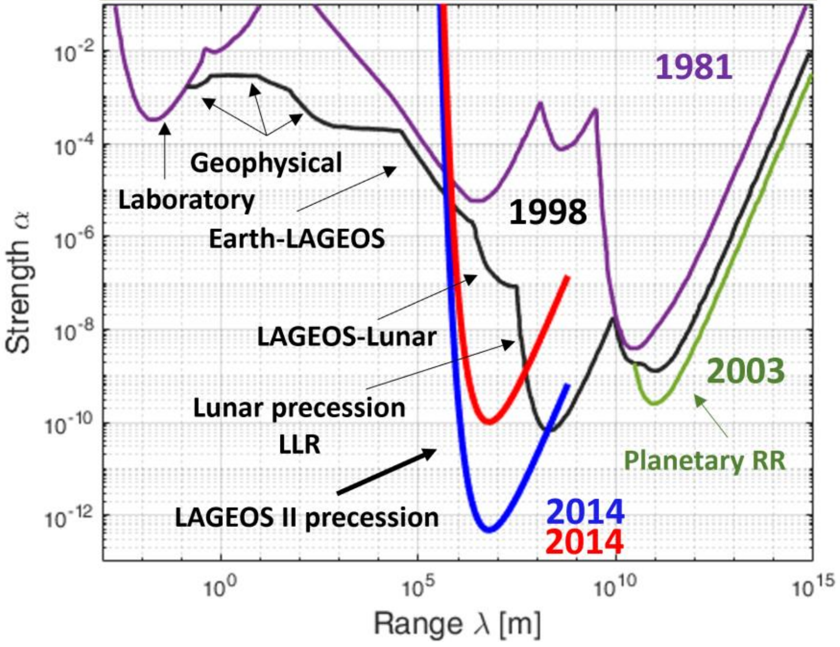
G_∞ = Newtonian gravitational constant;

r = Distance;

α = Strength of the interaction; K_1, K_2 = Coupling strengths;

λ = Range of the interaction; μ = Mass of the light-boson;

h = Planck constant; c = Speed of light



Previous limits with **LAGEOS's** from **GM** measurements:

$$|\alpha| < 10^{-5} \div 10^{-8}$$

$$|\boldsymbol{\alpha}| \cong \mathbf{5} \cdot \mathbf{10^{-13}}$$

$$|\boldsymbol{\alpha}| \cong \mathbf{1} \cdot \mathbf{10^{-10}}$$

D.M. Lucchesi, R. Peron, *Accurate measurement in the Field of the Earth of he General-Relativistic Precession of the LAGEOS II Pericenter and New Constraints on Non-Newtonian Gravity*, Phys. Rev. Lett. 105, 231103, 2010

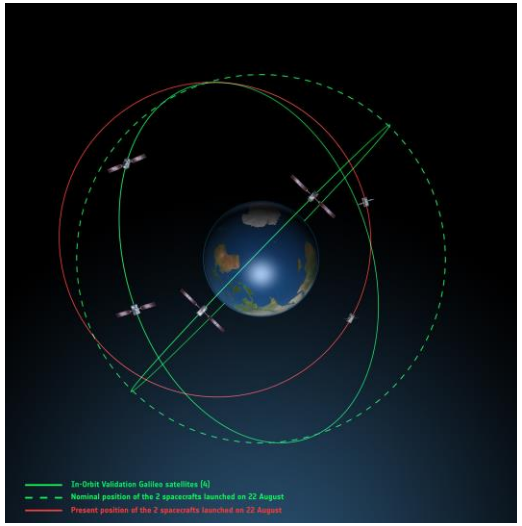
D.M. Lucchesi, R. Peron, *LAGEOS II pericenter general relativistic precession (1993-2005): Error budget and constraints in gravitational physics*. Phys. Rev. D 89, 082002, 2014

G4S_2.0

The **Galileo for Science** (**G4S_2.0**) project, funded by **ASI**, aims to perform a set of measurements in the field of **Gravitation** with the two **Galileo-FOC** satellites on **eccentric orbits** and taking advantage of the accuracy of their on-board **atomic clocks**

The **high level goals** of the project are:

1. A new measurement of the **Gravitational Redshift**
2. A measurement of the **General Relativity precessions** on the orbits of the satellites
3. Constraints on **Dark Matter**
4. Realise a pure **Relativistic Positioning System**
5. Detection of **Gravitational Waves** with the **Galileo-system**

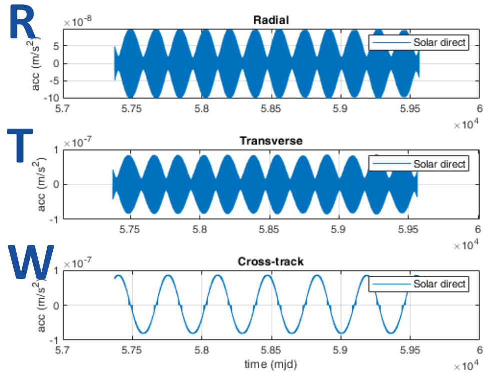


Other **fundamental goals** of the project are:

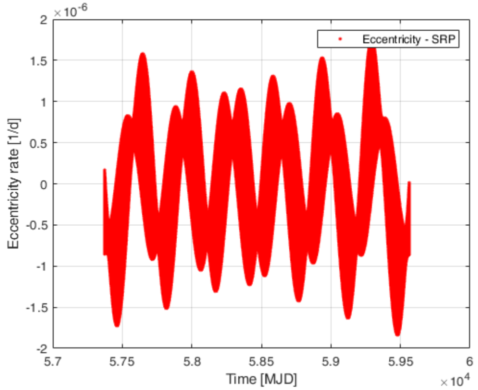
1. To develop new and more accurate models for the **Non-Gravitational Perturbations**
2. To develop a new **accelerometer concept** for a next generation of Galileo satellites

G4S_2.0

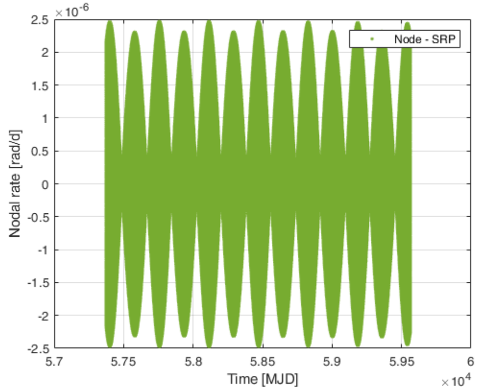
Gauss accelerations



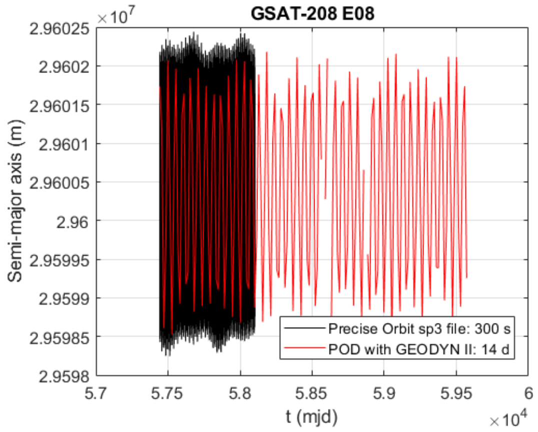
$$\frac{de}{dt} = \frac{\sqrt{1-e^2}}{na}[R \sin f + T(\cos f + \cos u)]$$

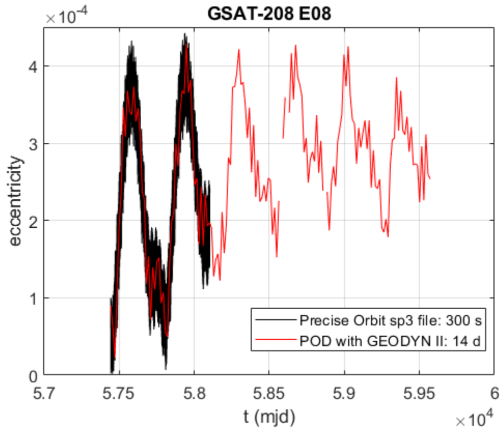


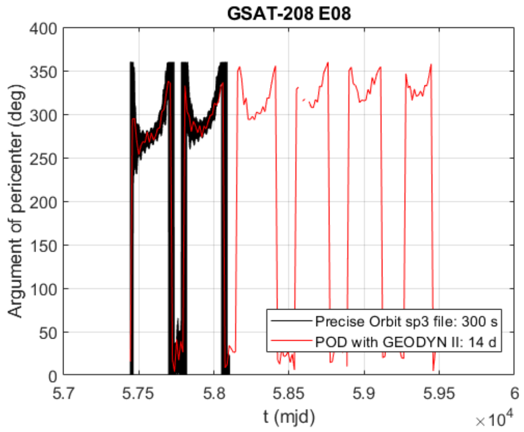
$$\frac{d\Omega}{dt} = \frac{W}{H \sin i} r \sin(\omega + f)$$



Box-wing model for GSAT-0208 (ESA Galileo metadata)



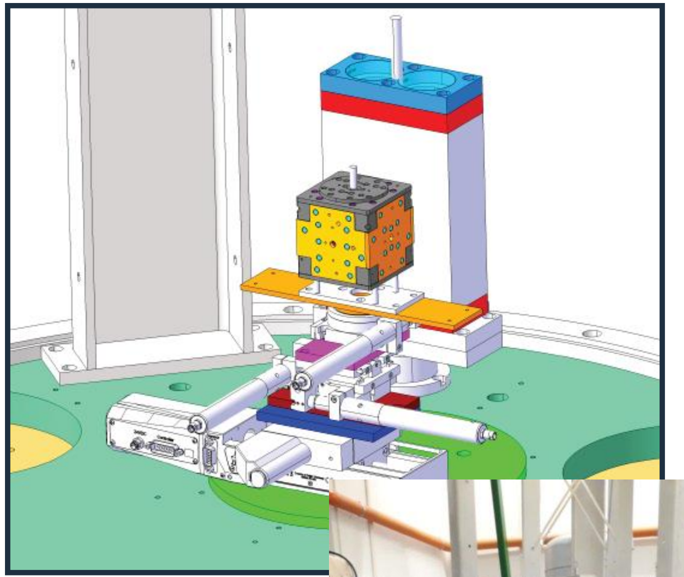


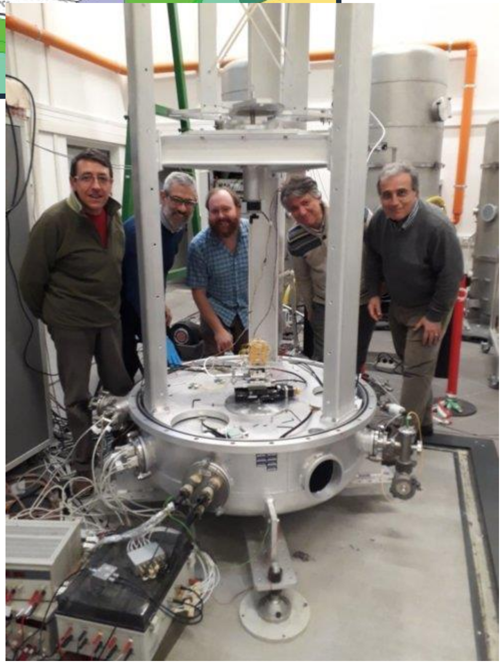


POD for GSAT-0208 vs ESA precise orbits

Liquid Actuated Gravity (LAG)

- R&D funded by INFN aimed at developing a new actuation technique for **laboratory tests of 1/r^2 gravitation force**, with possible **constraints on Yukawa-type interactions** on cm and sub-cm scale
- The basic idea is using as gravitational field source a container in which **the liquid level can be changed in a controlled and repeatable way** in order to modulate the force on a test mass, suspended from a torsion pendulum; with the proposed technique it is possible to **modulate the gravitational force without moving parts in the surroundings of the apparatus**
- The experimental apparatus uses two cylindrical containers in which the water level is modulated (field source) and an aluminium cube suspended from a double LISA-like torsion pendulum (test mass)





METRIC mission concept

Core on-board instrumentation (baseline)

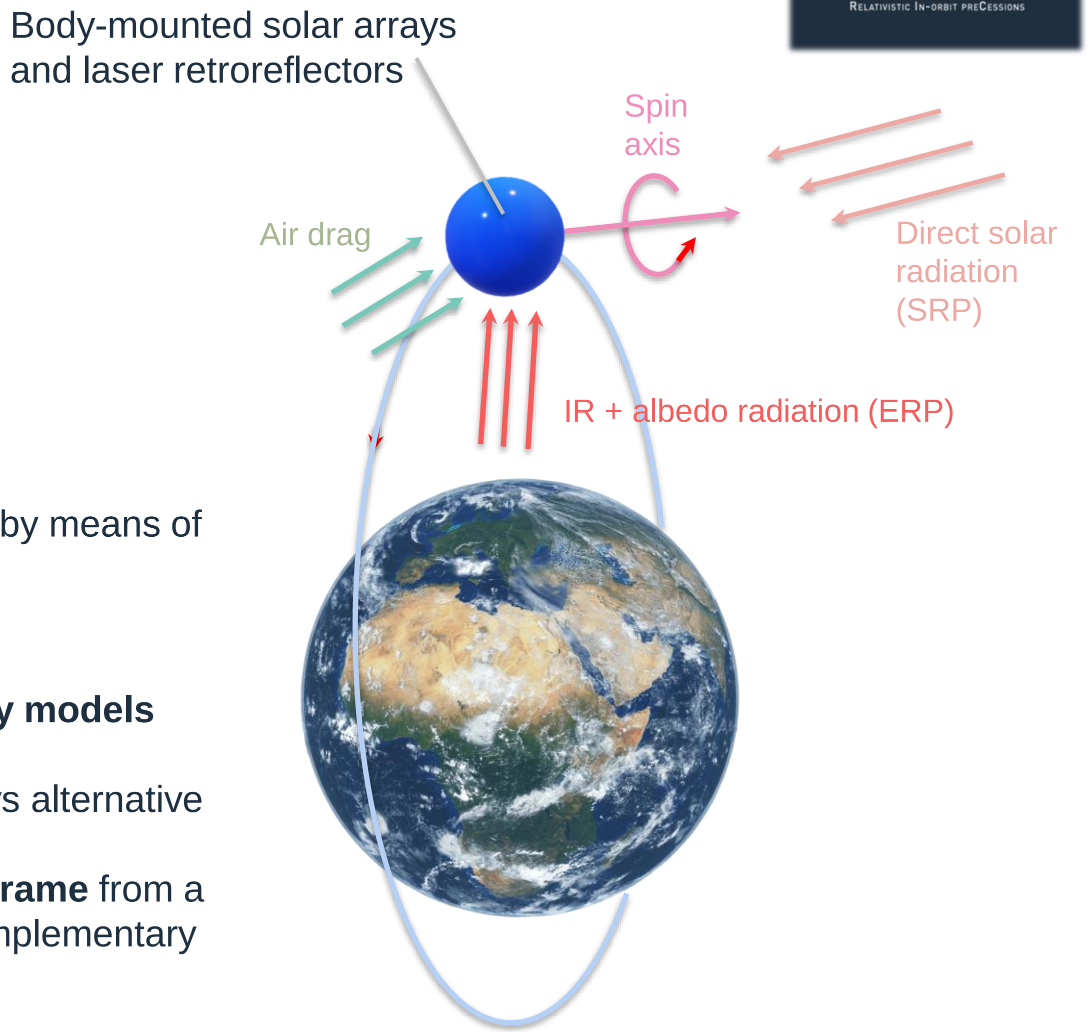
- **3-axis accelerometer** for **NGP measurement**
- Corner cube laser **retroreflectors** for **SLR**
- **GNSS** receiver
- Vacuum pressure ion-gauge

Strategy

- **Polar eccentric orbit (preliminary: 400/450 km x 1200 km)**
- Tracking with at least two **space geodetic techniques**
- **Virtual drag-free** spacecraft through acceleration data
- Modulation of acceleration signal via **slow spin**
- Separation of atmospheric drag and solar radiation pressure is achieved by means of acceleration measurement near apogee

International context

- **Upper atmosphere** Strong need for **reliable upper atmosphere density models** (satellite lifetime, collision avoidance maneuvers)
- **Fundamental physics** Testing the law of **gravitation** (general relativity vs alternative theories)
- **Geodesy / ITRF** Requirement of a more accurate **terrestrial reference frame** from a host of disciplines (astronomy, navigation, Earth System sciences) – Complementary and synergistic with the ESA GENESIS programme



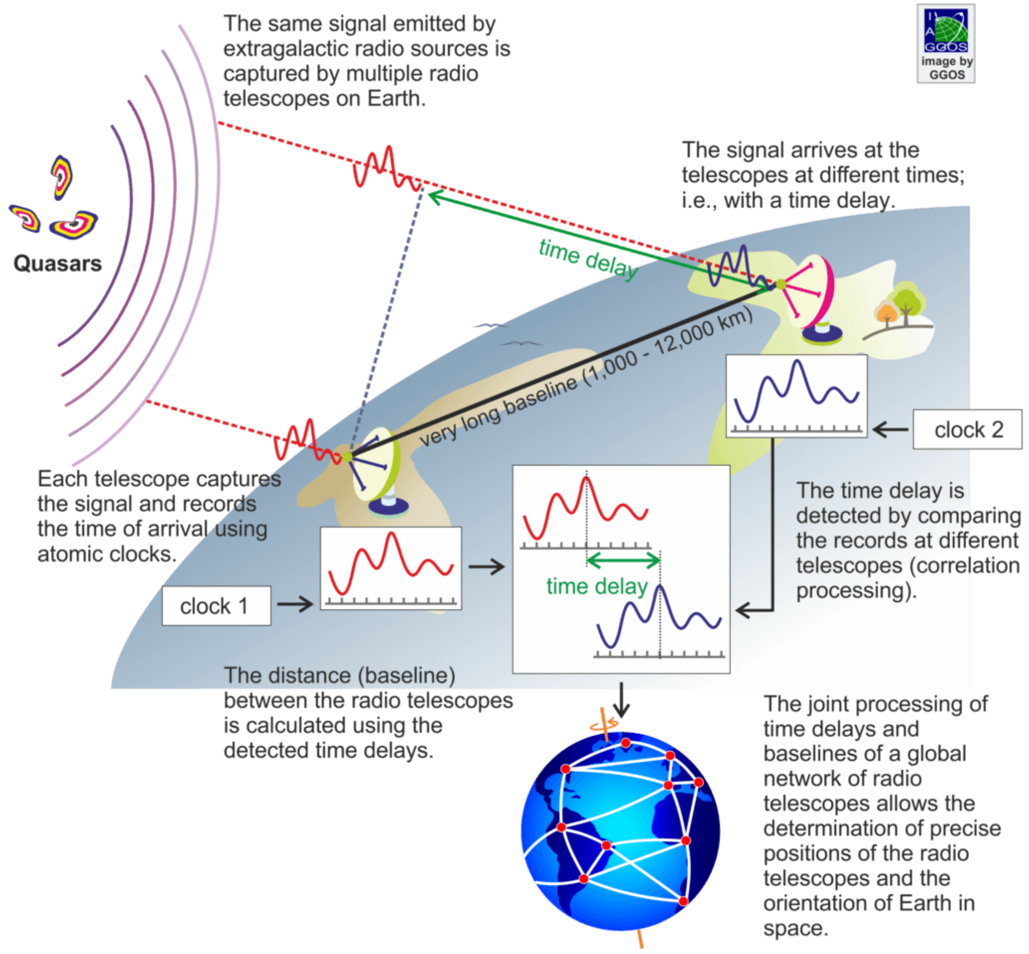
Geodetic VLBI

VLBI observes extragalactic sources with a network of large (12 m to 30 m) paraboloidal antennas at centimeter radio wavelengths to determine **precise positions of the radio telescopes** and the **Earth Orientation Parameters**.

Two VLBI networks in operation:

– Legacy S/X (since approximately 1980)
  Larger, generally slower antennas with analog electronics

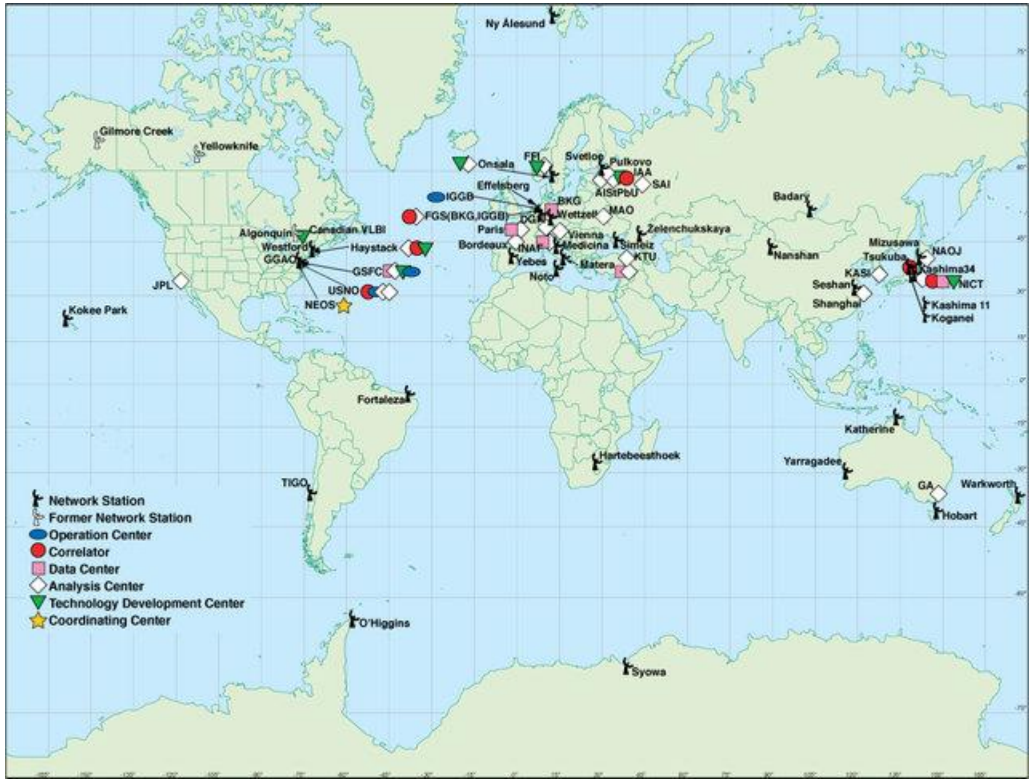
– The newer VLBI Global Observing System (VGOS)(since 2015)
  Generally smaller, faster antennas with modern digital signal processing



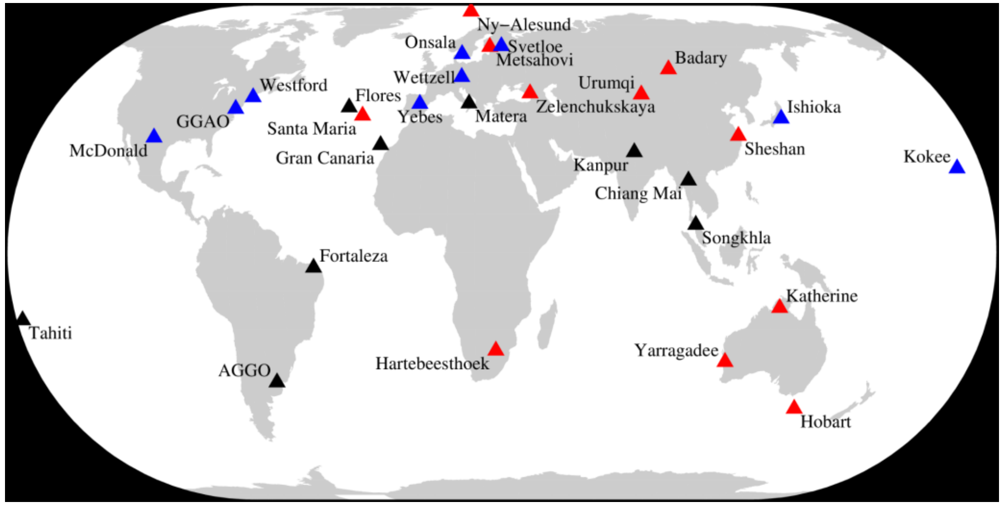
Monia Negusini, Claudio Bortolotti, Marcello Giroletti, Giuseppe Maccaferri, Federico Perini, Juri Roda, Mauro Roma, Pierguido Sarti, Carlo Stanghellini, Matteo Stagni, Giampaolo Zacchiroli

Roberto Ricci, Roberto Ambrosini, Vincenza Tornatore

Geodetic VLBI



Legacy S/X International VLBI Service
for Geodesy and Astrometry (IVS) network



VLBI Global Observing System
(VGOS) IVS network

▲ Operational ▲ antenna built, signal chain in work needed ▲ in planning stage

VLBI and metrology

- The Italian Quantum Backbone (IQB) is an infrastructure to deliver a **frequency standard signal** from the Italian metrological Institute (INRIM) to remote locations via an optical fiber link with **unprecedented stability** (order of 10^{-19})
- **Geodetic VLBI experiments** were performed in 2015-2018 with remote frequency standard provided by INRIM to the Medicina station with ten's of ps wrms residuals in group delay: on par with experiments using local clocks (Clivati et al. 2017)
- IQB reached Matera Centre for Space Geodesy in Nov 2018 covering a fibre optic span of 1800 km: the 1st **common clock experiment** connecting Matera and Medicina stations was carried out in May 2019 (Clivati et al. 2020) and followed up in Jan 2021
- Interferometric phase noise was used in **remote and local clock timing experiments** with radio and geodetic VLBI set-ups between Jan 2018 and Feb 2021: phase scatters down to 2 ps were found on the best performing baselines
- Two portable small (2.4-m) antennas in combination with the large Japanese Kashima 34-m antenna have been used in 2018-19 to **compare optical lattice clocks** between INRiM (Italy) and NICT (Japan) via the VLBI technique down to a frequency relative uncertainty of a few in 10^{-16} (Sekido et al. 2021; Pizzocaro et al. 2021)
- In collaboration with the Korean institutes KASI, SGOC and KISTI an **observing geodetic VLBI campaign** has started in Dec 2021 to **compare optical lattice clocks** between INRiM (Italy) and KRISS (Korea) with a final goal of $\Delta\nu/\nu$ of 10^{-17} when the Compact Triband Receivers will be installed on the Medicina antenna

VLBI and metrology
Italian Quantum Backbone

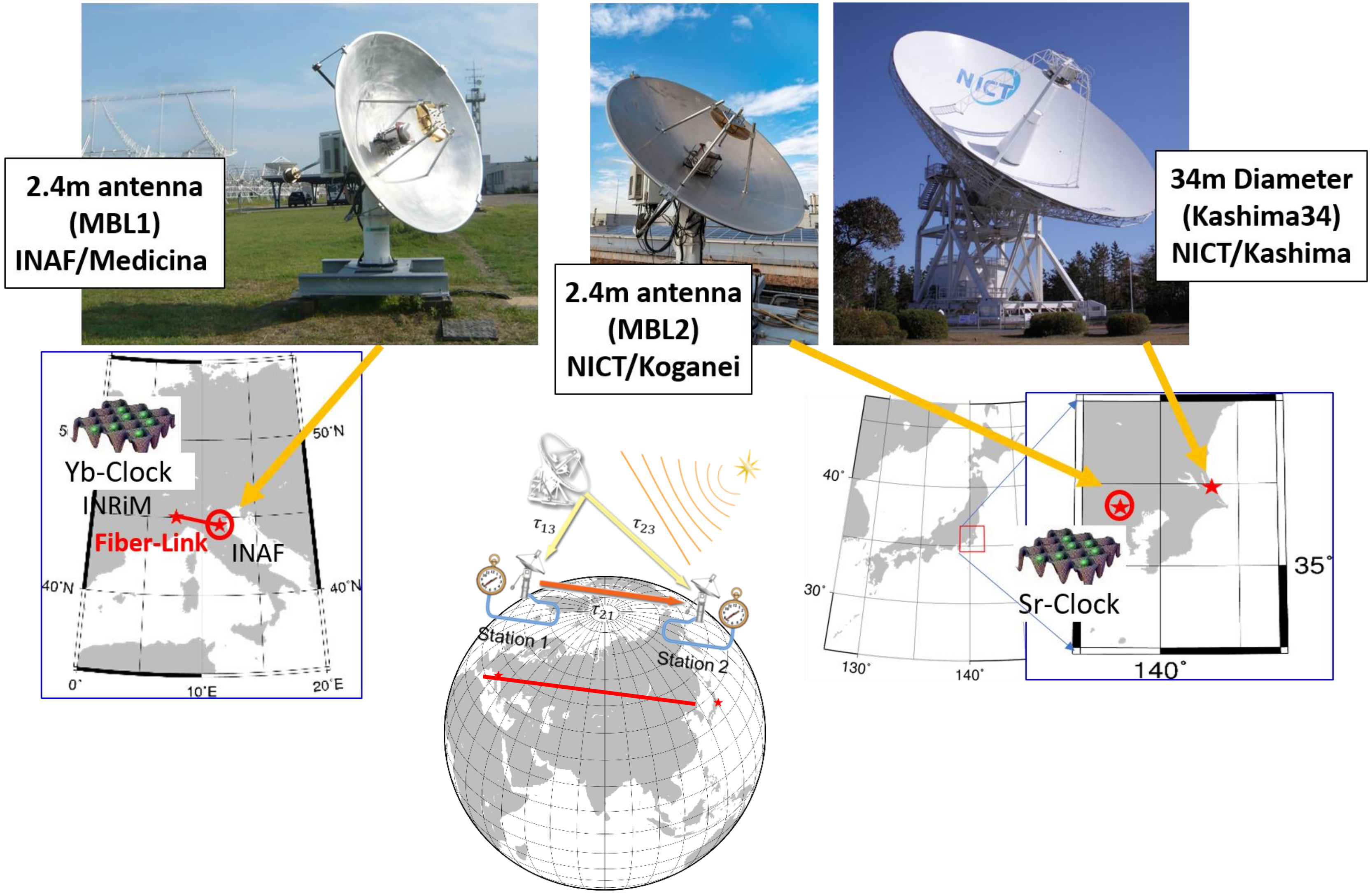
Italian link extension

→ 1800 km divided into 4 spans

At each terminal:

- Regeneration laser
- Fiber noise compensation
- Ultrastable laser available

VLBI and metrology
Optical clock comparison via broadband VLBI



Relativistic astrometry

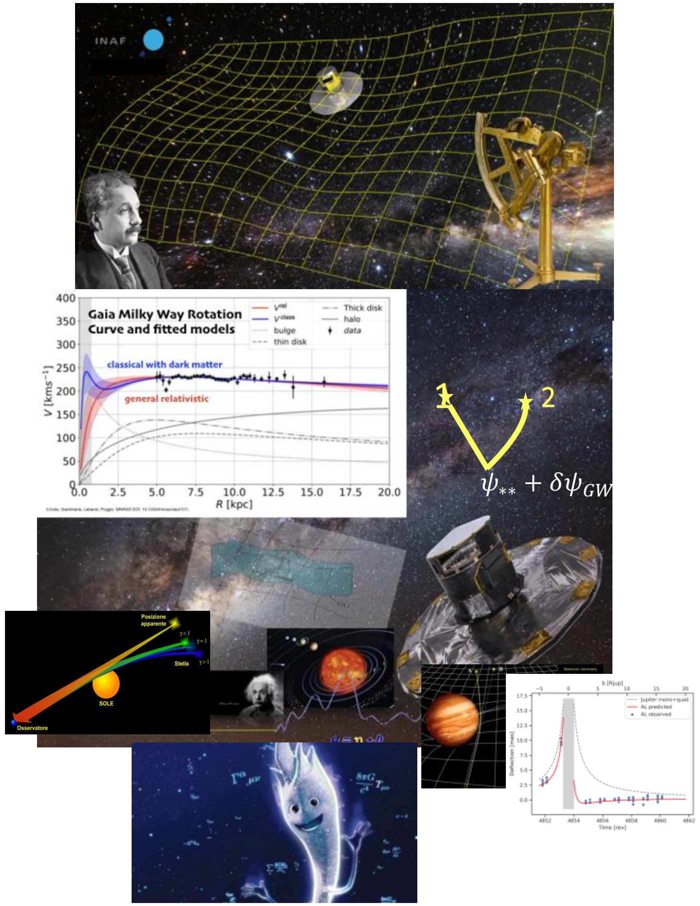
LOCAL COSMOLOGY

The Galaxy as product of fundamental physics, from Solar System to its outskirts (RSN2)

RELATIVISTIC ASTROMETRY theoretical, analytical and / or numerical models, completely based on General Relativity (GR) + relativistic attitude (satellite or ground based observers) for data analysis and processing of increasingly accurate astronomical data

GRAVITATIONAL ASTRONOMY **consistent application of GR from the scales of the Solar System to those of the Milky Way [i.e. gravitational metrology for astrophysics and cosmology]**
- relativistic effects on photon trajectories also due to BHs; measurement of light deflection due to planets (GAREQ experiment), tests on PPN gamma and beta parameters
- GR (kinematics & dynamics) models for the Milky Way, tests on GR theory and alternative gravity theories, role and nature of dark matter and dark energy
- spacetime navigation, nature of time

ASTROMETRIC GRAVITATIONAL WAVE ANTENNA astrometric identification of gravitational waves and instantaneous measurement of their direction within sub-arcs based on the advancement of relativistic models already successfully used for the analysis of Gaia mission data; synergies also with Pulsar Timing Array



Synergies with all RSNs in INAF, University INRIM and INFN; Third mission

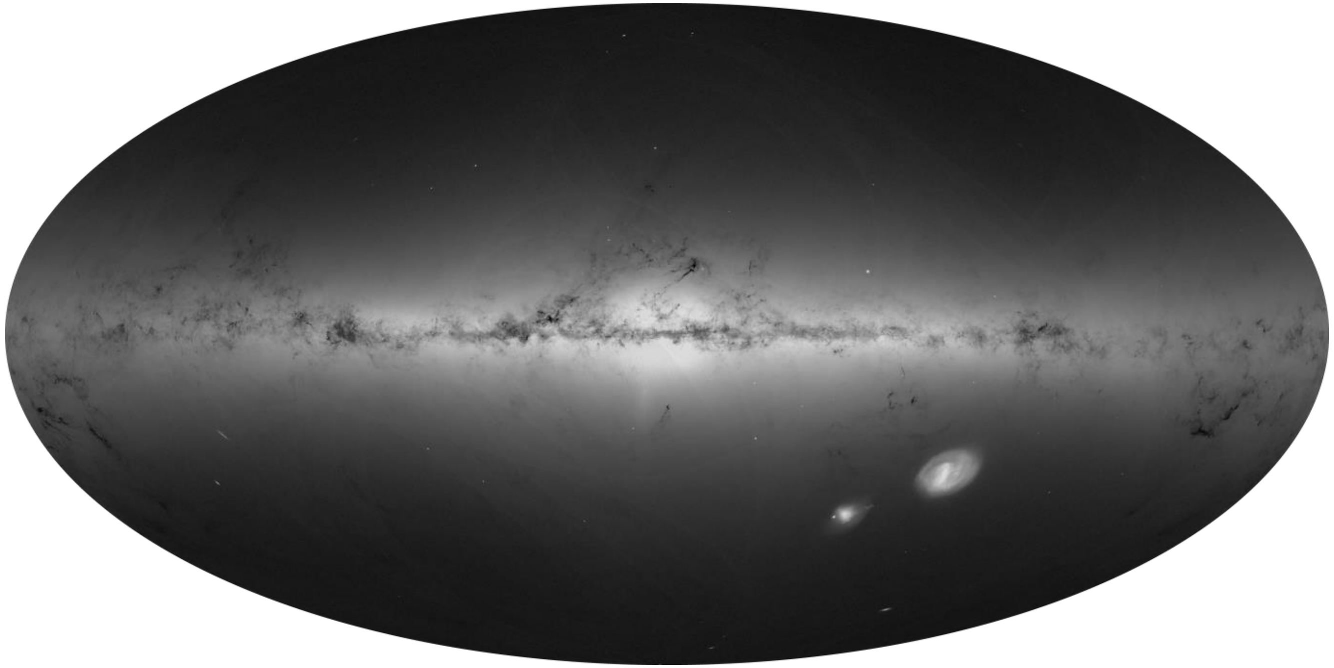
Details in schede&audizioni:
GraviMetrA (*Gravitational Metrology & Astronomy), BLUE_Gang,* PI Mariateresa Crosta
GaiaUniverse, PI Mario G. Lattanzi
ASTRA, PI Mario Gai

Multidisciplinary skills (theoretical and technological) developed over 30 years in the context of the Hipparcos and Gaia missions by INAF staff in which they play a leading role in defining the scientific and technological aspects with the fundamental support of ASI. In particular:

INAF U.Abbas, S.Bertone, B. Bucciarelli, R. Buzzi, D. Busonero, V.Cesare, M.Crosta, M.Gai, M. G.Lattanzi, R. Morbidelli, P. Re Fiorentin, A. Riva, A. Spagna, A. Vecchiato, M. Sarasso
Dottorandi W.Beordo (UNITo), F. Santucci (UNITo)
Collaboratori associati **V. Akhmenatov (Kharazin University), A. Butkevich (Pulkovo Observatory), L.Shilong, Qi Zhaoxiang (CAS@SHAO), A. Tartaglia**

Relativistic astrometry

Map of the Galaxy



Research field inaugurated with the advent of Gaia to guarantee its scientific products: **essential for future missions operating in space and for the definition of celestial reference systems** fully compliant with GR

2023 Lancelot M. Berkeley - New York Community Trust Prize for Meritorious Work in Astronomy for the Gaia collaboration

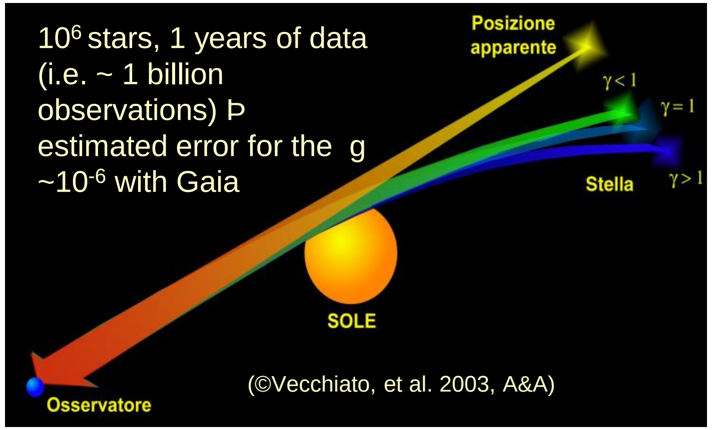
More than 250 publications per month, about 20% with INAF leadership or strong contribution

- M. Crosta et al. “General relativistic observable for gravitational astrometry in the context of the Gaia mission and beyond” Phys. Rev. D 96 2017
- A. Vecchiato et. al, The global sphere reconstruction (GSR). Demonstrating an independent implementation of the astrometric core solution for Gaia, A&A 2018
- M.Crosta.“Astrometry in the 21st century. From Hipparchus to Einstein”. In: La Rivista del Nuovo Cimento 42 (2019) and references therein

Relativistic astrometry
Gravitational astronomy @Solar System scale

Relativistic astrometry implies a full general-relativistic analysis of the light trajectory, from the observer to the star, including any type of celestial objects

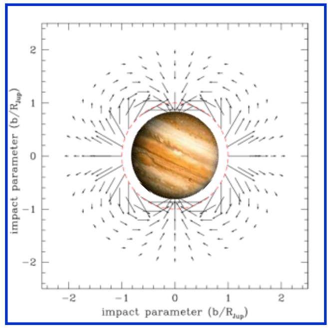
Global astrometry



PPN-gamma parameter as a by-product of the sphere reconstruction and screening for alternative theories of gravity

This started in 2003 with the first end-to-end simulation of a Gaia-like mission aimed to estimate the potential accuracy of such kind of a mission (Vecchiato et al., A&A, 620, 2003) and is continuing today with a series of papers that are investigating in detail the correlation between this parameter and the parallaxes in a Gaia-like mission (Butkevich et al., A&A, 603, 2022, Butkevich et al., in preparation)

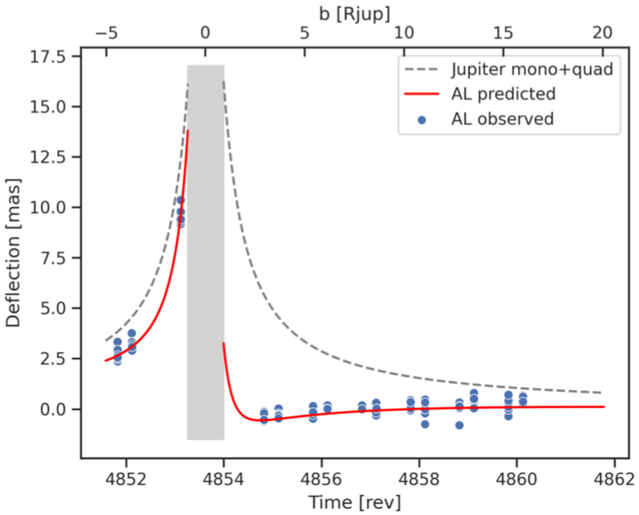
Differential astrometry



GAREQ (GAia Relativistic Experiment on Quadrupole, light deflection by Jupiter's quadrupole)
Crosta and Mignard (Class.Quant.Grav.23:4853-4871,2006)

->#Gaia spin axis orientation optimised to catch a star close to the limb of Jupiter in 2017 for a precise light deflection measurement.

First observation of light deflection due to Jupiter



(From Abbas, Bucciarelli, Lattanzi, Crosta, Busonero et al. , 2021, *Differential Astrometric analysis of the GAREQ experiment: Detection of the strongest Jupiter deflection signal with Gaia, A&A* , 2022, 10.1051/0004-6361/202243972)

Relativistic astrometry
Gravitational astronomy @Milky Way scale

GR and Classical MILKY WAY ROTATIONAL CURVEs

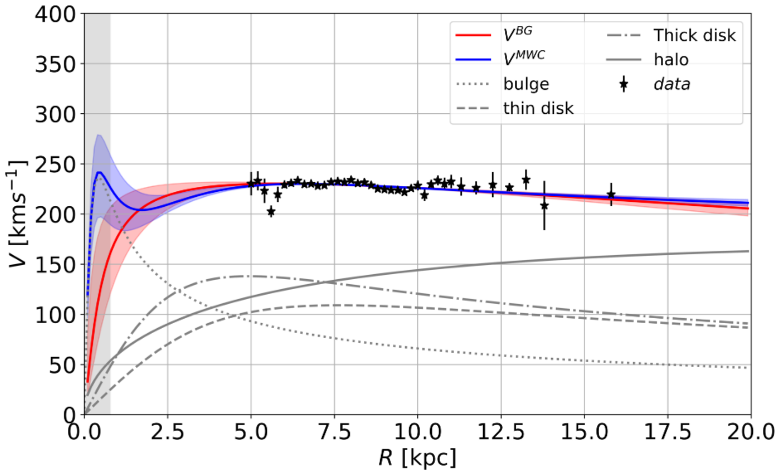
MCMC fit to the Gaia DR2 data

https://www.cosmos.esa.int/web/gaia/iow_20200716)

Details: On testing CDM and geometry-driven Milky Way rotation curve models with *Gaia* DR2
Crosta M., Giammaria M., Lattanzi M. G., Poggio E.,MNRAS, Volume 496, Issue 2, August 2020

Red: GR Velocity profile

Blu: Classical Velocity profile comprising a bulge, disk and halo



The two models appear

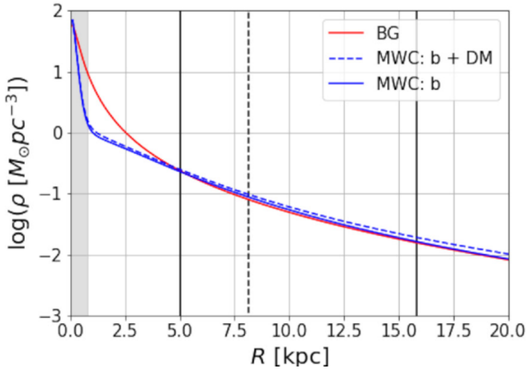
almost identically

consistent with the data

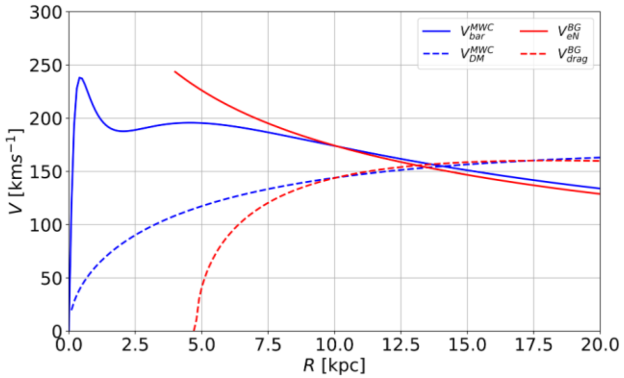
This favourably points to the fact that a gravitational dragging-like effect (*i.e.* geometry) could sustain a flat rotation curve

Confirmation with DR3
(W.Beordo, M.Crosta, MG Lattanzi, P. Re Fiorentin, A. Spagna, in submission)

The baryonic density profile via Einstein field eq.



Dragging effect vs. halo effect



Relativistic astrometry

ASTROGRAWANT

ASTROmetric GRAvitational Wave ANTenna

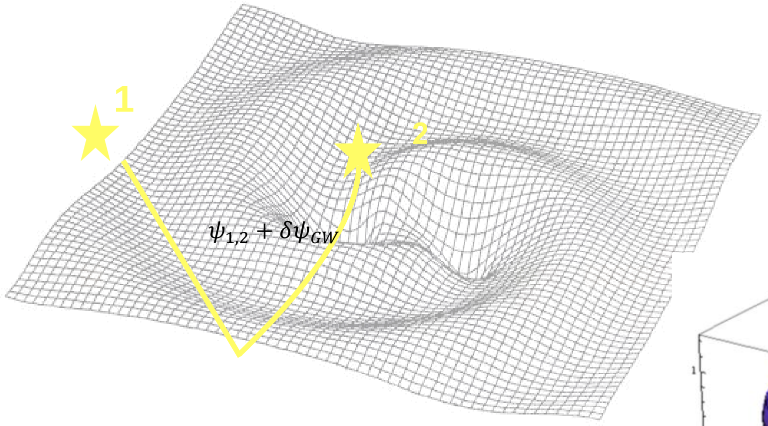
- AstroGraWAnt is based on close pairs of point-like sources as natural antenna "arms" to record the very tiny variations in their angular separations induced by passing gravitational waves (GWs): all-differential formulation of the astrometric observable
- The GW observability is AMPLIFIED through a factor depending on the angle between the unperturbed directions to star-like objects that acts as a ``signal amplifier'' for the GW detection, limited only by the resolving power of the optics

M.Crosta, Rivista del Nuovo Cimento 42, 10 (2019)

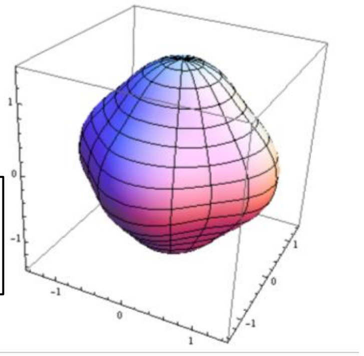
M.Crosta, M.G. Lattanzi, C. Leponcin-Lafitte, M. Gai, Q. Zhaoxiang, A.Vecchiato,

On the principle of Astrometric Gravitational Wave Antenna, 2022 submitted, https://arxiv.org/pdf/2203.12760.pdf

F. Santucci, M. Crosta, M. G. Lattanzi, *Angular sensitivity of Astrometric Gravitational Wave Antenna,* in submission



Differential formulation along 3 directions: $\delta\psi \propto h^{GW}/\psi$



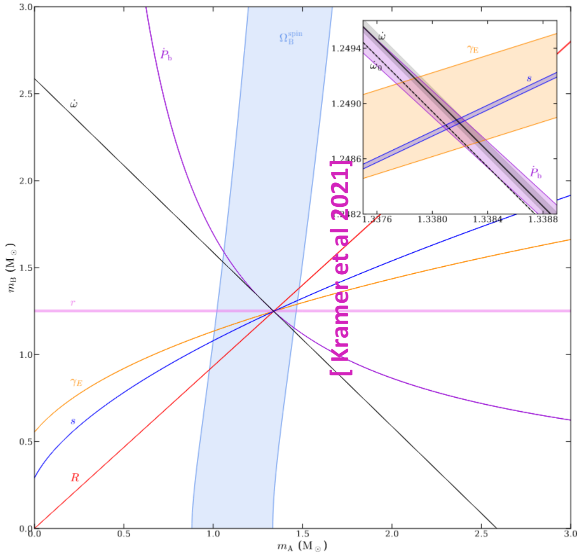
Fundamental physics with Pulsars

Cagliari Pulsar Group – Constraining GR

The Double Pulsar J0737-3039A/B [Burgay et al. 2003, Lyne et al 2004] remains the best laboratory for precision measurements

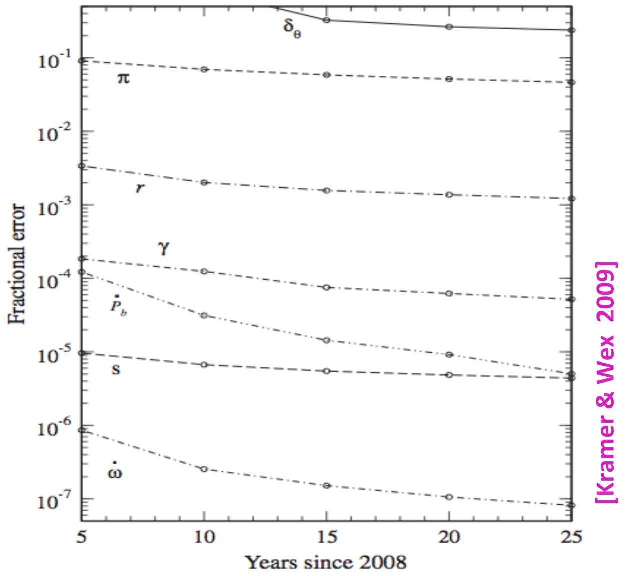
Spin period (ms) = 22.69937898647277 ± 0.00000000000008 (measured to 80 atto-seconds)

Orbital period (d) = 0.102251562473 ± 0.000000000001 (i.e. 2.45h measured to 86 nano-seconds)



A factor ≈ 25 better than the Nobel-prize system in constraining the RADIATIVE predictions of GR [Kramer et al. 2021]

Moreover the fractional error for all the relativistic parameters will keep improving with time



Effects of retardation and aberrational light-bending have been observed for the first time in this system and have allowed us to determine the spin direction of the pulsar.

Seven (!) post keplerian parameters have been measured. The measurement precision is so high that for the first time we had to take higher-order contributions into account for some of them.

e.g the contribution of the A pulsar's effective mass loss (due to spin-down) to the observed orbital period decay, a relativistic deformation of the orbit, and the effects of the equation of state of super-dense matter had to be included. [Kramer et al. 2021]

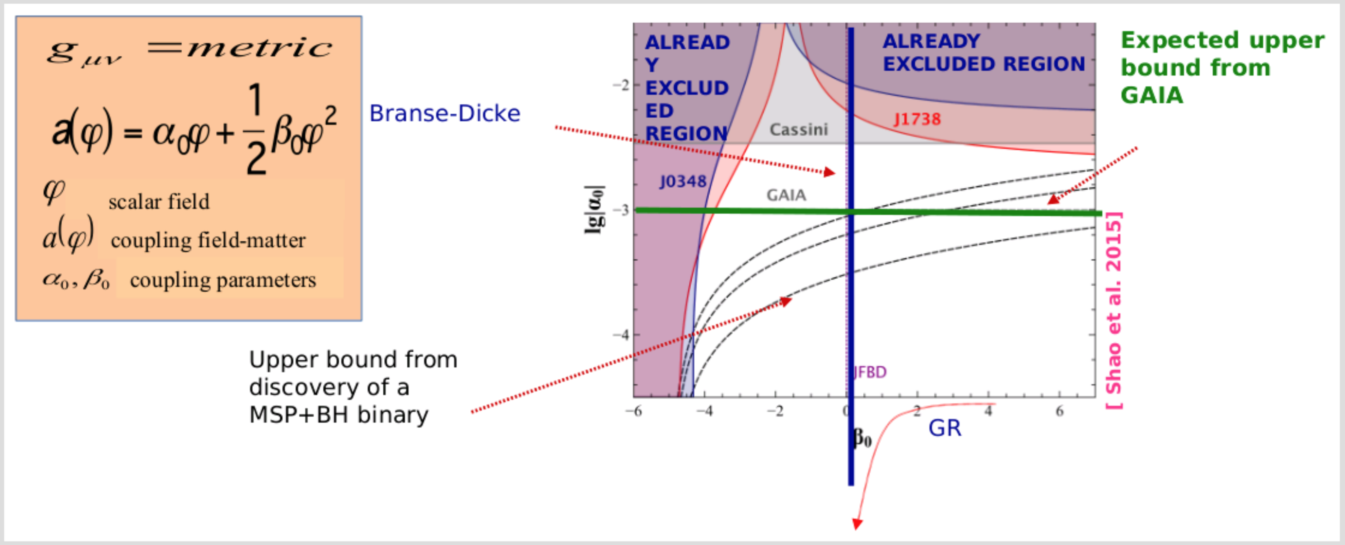
Fundamental physics with Pulsars

Cagliari Pulsar Group – Constraining alternative theories

Tensor-scalar theories predicts the emission of a large amount of DIPOLAR scalar waves (as opposed to the dominant QUADRUPOLAR radiation predicted by GR) in binaries with a high asymmetry in the the degree of compactness ε (i.e. in the self-gravity) of the two bodies

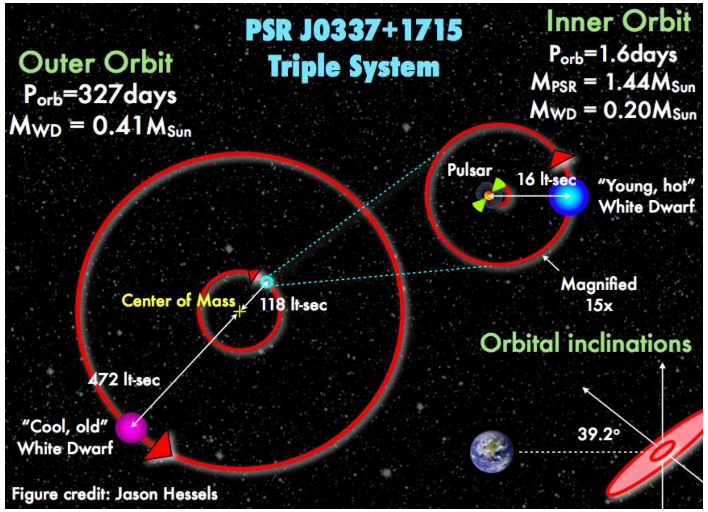
$$\varepsilon_{NS} = \left|\frac{E_{grav}}{E_{rest}}\right| = \frac{GM_{NS}}{c^2 R_{NS}} \cong 0.2 \qquad \varepsilon_{WD} = \left|\frac{E_{grav}}{E_{rest}}\right| = \frac{GM_{WD}}{c^2 R_{WD}} \cong 10^{-4}$$

In fact, NS+WD binaries (like J1738+0333 and J0348+0432) for which one can measure or constrain the orbital decay and the masses are the best available systems for constraining the coupling constant α_0 in tensor-scalar theories [Esposito-Farese 2005; Freire et al 2012]



Fundamental physics with Pulsars

Cagliari Pulsar Group – Constraining principles and constants



[© Hessels 2014]

The **Strong equivalence principle (SEP)** can be tested by precisely measuring the orbital motion of the inner NS+WD binary in the strong gravitational field of the outer orbiting WD in the **triple system J0337+1715**

Few tens of such systems are expected to be in the Galaxy and discovered in the future with SKA and SEP tested with exquisite precision

Einstein equivalence principle (EEP), namely the local Lorentz invariance **(LLI)** of gravity and the local position invariance **(LPI)** of gravity, are nowadays best constrained with pulsar timing experiments. These constraints will improve a factor 10-50 with next generations SKA experiments

The constraints on **time-variation of the gravitational constant G** [Freire et al. 2012], from observations (both VLBI [Deller et al. 2008] and timing [Verbiest et al. 2008]) of the pulsars J0437−4715 and J1738+0333, are already comparable to the best constraints from the Solar System experiments [Will 2014]. Pulsar-derived limits will improve significantly, and pulsar tests are sensitive also to strong-field effects on $\dot{G}$ [Wex 2014]

Fundamental physics with Pulsars
Cagliari Pulsar Group – Perspectives

Finding and timing a PSR-BH binary
(and maybe a PSR-MSP binary in a Globular Cluster [Clausen et al. 2014])

From M & S $\chi \equiv \frac{c}{G}\frac{S}{M^2}$

$\chi <= 1$ ***Test of Cosmic Censorship Conjecture*** *[Penrose 1969]*

Finding and timing a PSR closely orbiting Sgr A*

From M & Q $q \equiv \frac{c^4}{G^2}\frac{Q}{M^3}$

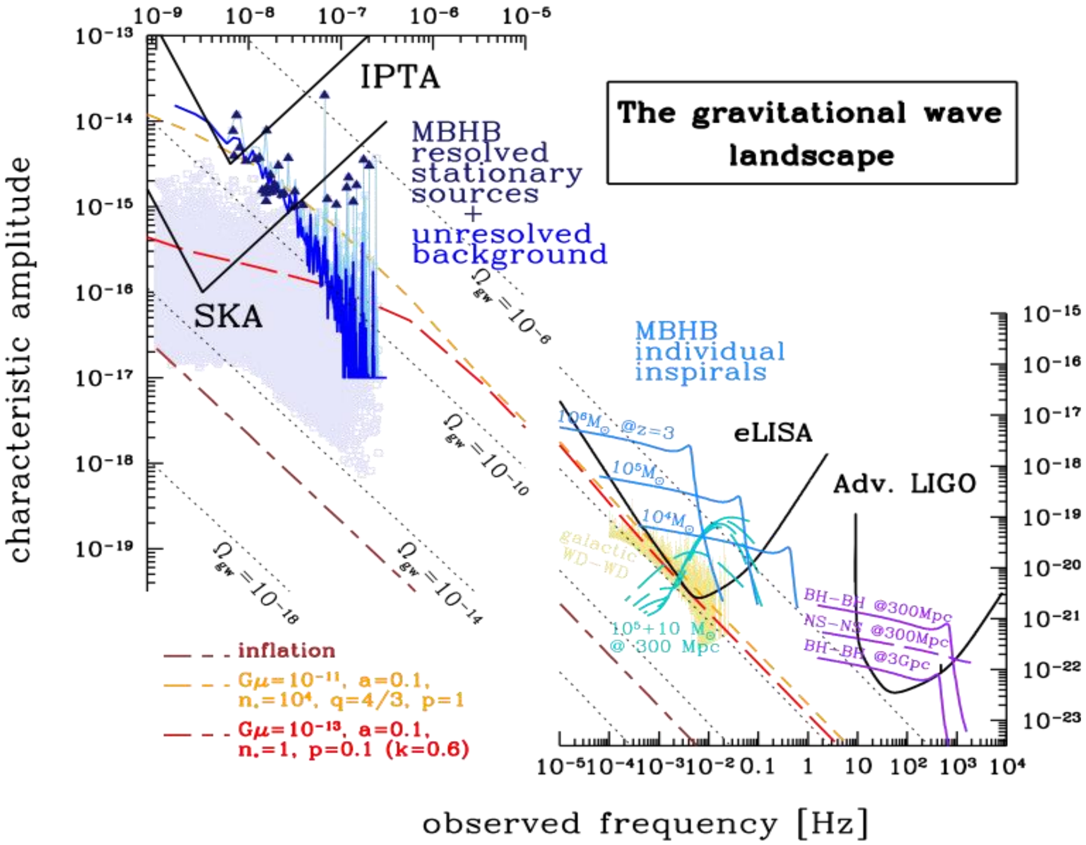
$q = -\chi^2$ ***Test of No Hair theorem***

The EoS of nuclear matter uniquely determines several NS observables:
M-R relation, moment of inertia I, cooling rate, minimum spin period P_{min} and maximum mass M_{max} above which NSs collapse to black holes.

Fundamental physics with Pulsars
Cagliari Pulsar Group – Pulsar Timing Array

Note the complementarity in explored frequencies with respect to the current and the future GW observatories, like advLIGO, advVIRGO and eLISA

- **Expected sources:**
  - **super-massive BH binaries in early Galaxy evolution**
  - **cosmic strings**
  - **cosmological sources**
- **Types of signals:**
  - **stochastic (multiple)**
  - **periodic (single)**
  - **burst (single)**



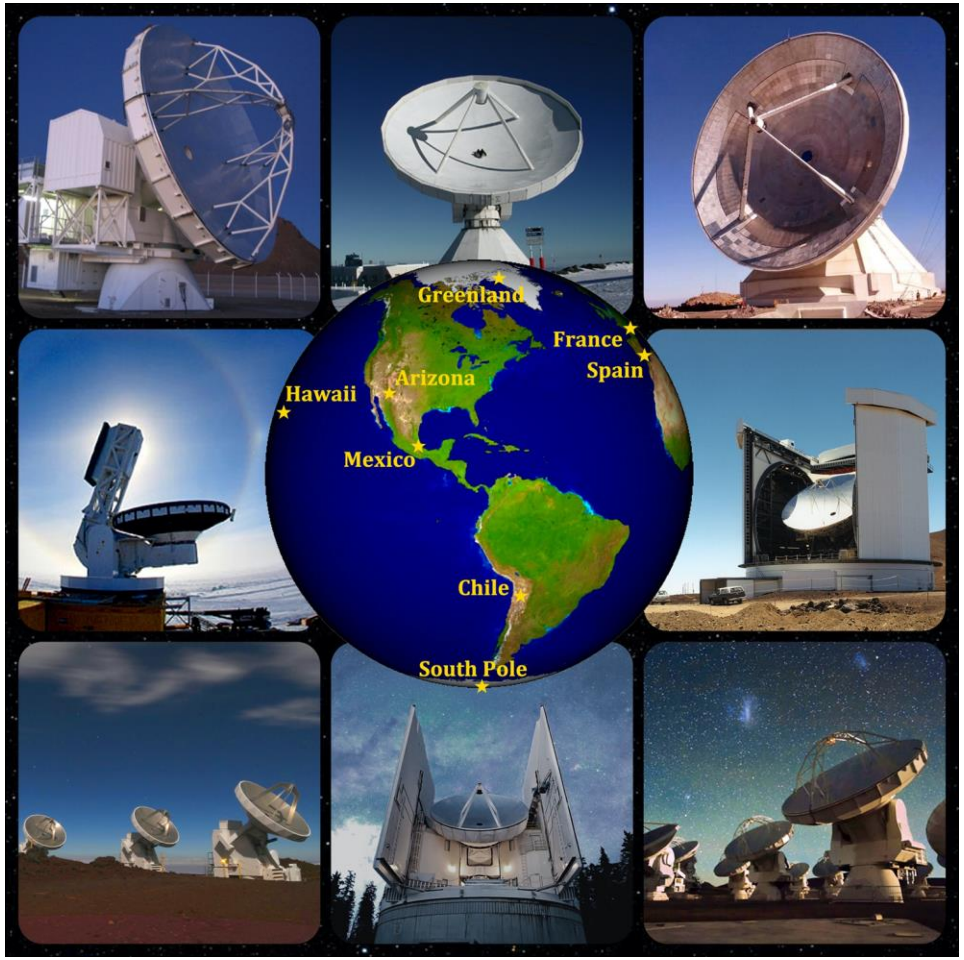
[Janssen et al 15]

Event Horizon Telescope (EHT)

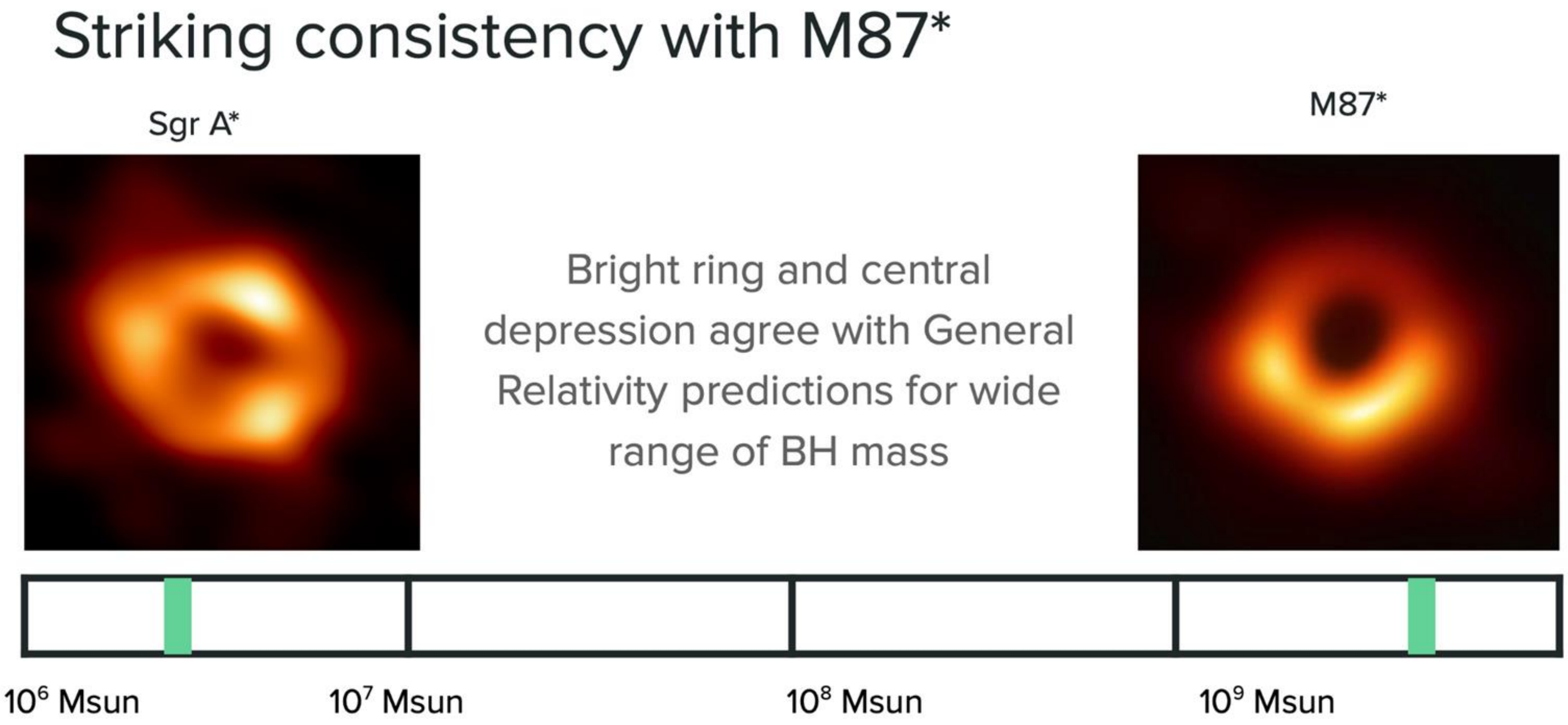
- **Largest global VLBI network** observing @1 mm
- Big international collaboration (> 300 members)
- INAF is an affiliated institute

- M87* and Sgr A* at event horizon scales.
  - Direct imaging of **BH shadows**
  - Study of **accretion processes around SMBH**
- AGN jets at ten of microarcsec scales:
  - Understand the **jet origin and collimation**
- Testing **General Relativity**
- Multiwavelength view of EHT targets

https://eventhorizontelescope.org/science

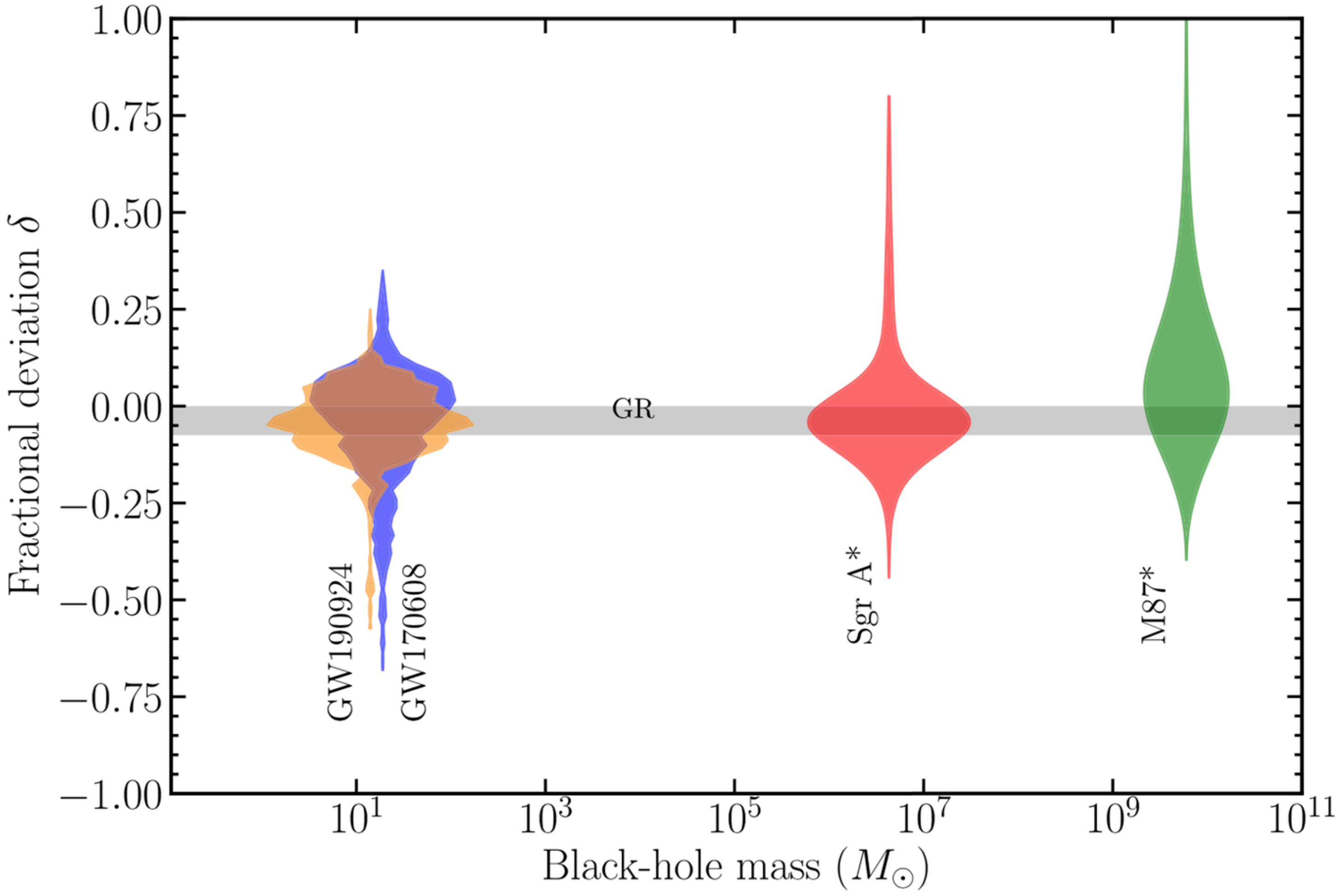


Event Horizon Telescope (EHT)



First direct proof of the existence of a **supermassive black hole** in the center of our Galaxy and in M87 (EHTC+ 2019a, 2022a)

Event Horizon Telescope (EHT)



GR confirmed over a range of mass scale

Kerr black hole nature confirmed by ring properties, presence of event horizon and exclusion of alternative objects through model comparisons

EHTC+ 2022f

Event Horizon Telescope (EHT)

Members of EHTC

Elisabetta Liuzzo (INAF-IRA): Calibration and Error WG, EHT Board guest member

Nicola Marchili (INAF-IRA): Time domain WG

Kazi Rygl (INAF-IRA): Calibration and Error WG, Publication Committee

Ciriaco Goddi (U. Cagliari, INAF-OAC affiliated): Time Domain WG coordinator

Mariafelicia De Laurentis (UniNA, INFN, INAF-OACN affiliated): Deputy Project Scientist, Gravitational Theories

Rocco Lico (IAA, INAF-IRA affiliated): ICT Officer and Secretary

Giacomo Principe (UniTS, INAF-IRA affiliated): Data analysis, Publication Committe

External members EHTC

Marcello Giroletti (INAF-IRA): EHT multiwavelength Science WG

IT EHTC fundings and INAF schede

INAF Schede:

- **EHT** (RNS4 primary, RSN1 and RSN5 secondary)

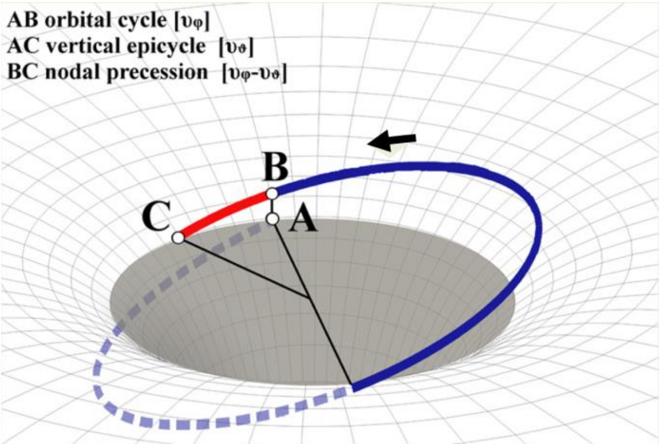
Fundings:

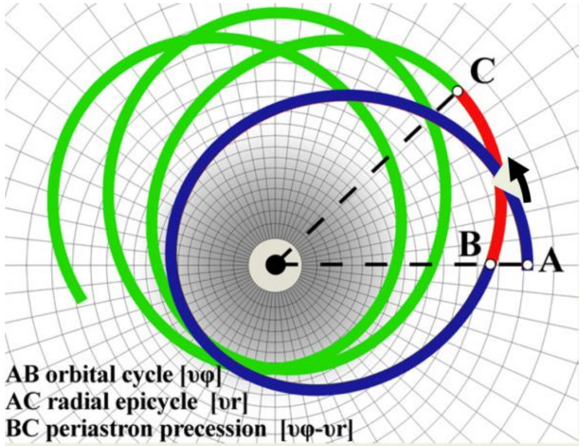
- **Past:** Funding from ERC BlackHoleCam (finished in July 2021)
- **Present:** No funding; INAF Large Grant proposal rejected, PRIN proposal results awaited.
- **Future:** Keep applying for funding!

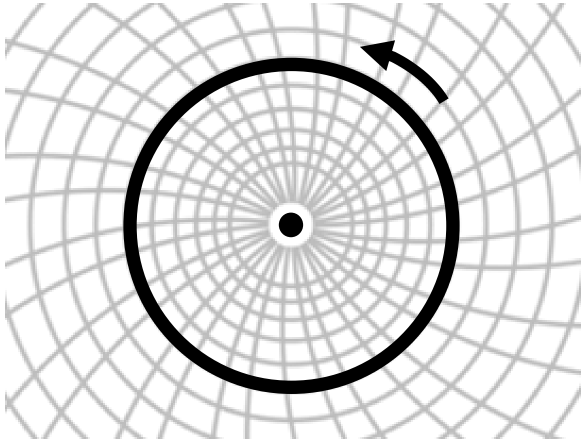
GR X-ray timing modelling

Relativistic precession model (RPM)

Lense-Thirring precession	Periastron precession	Orbital motion







Low-frequency QPO	Lower high-freq. QPO	Upper High-Freq. QPO

Application of a **relativistic precession model** (Stella & Vietri 1998, Stella et al. 1999) to **rapid X variability of BH binaries**

Orbital motion

$$\nu_\phi = \pm\frac{1}{2\pi}\left(\frac{M}{r^3}\right)^{1/2}\frac{1}{1\pm a\left(\frac{M}{r}\right)^{3/2}}$$

Periastron precession

$$\nu_{per} = \upsilon_\phi\left(1-\left(1-\frac{6M}{r}-3a^2\left(\frac{M}{r}\right)^2\pm 8a\left(\frac{M}{r}\right)^{3/2}\right)^{1/2}\right)$$

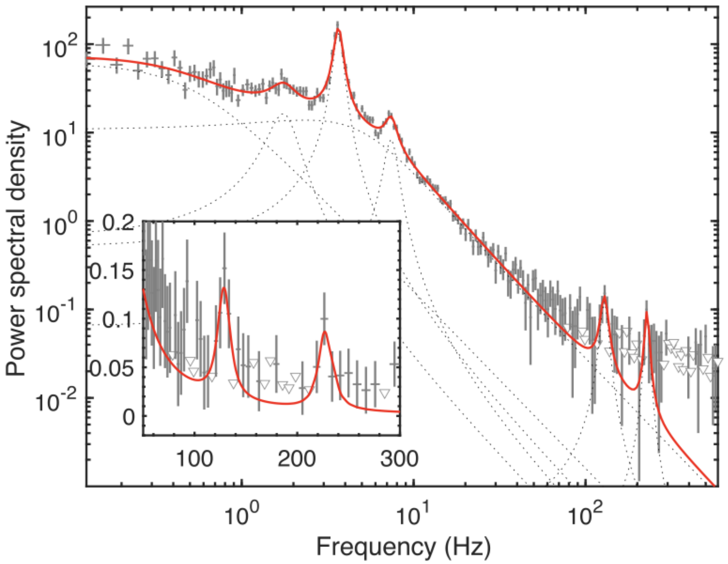
Lense-Thirring precession

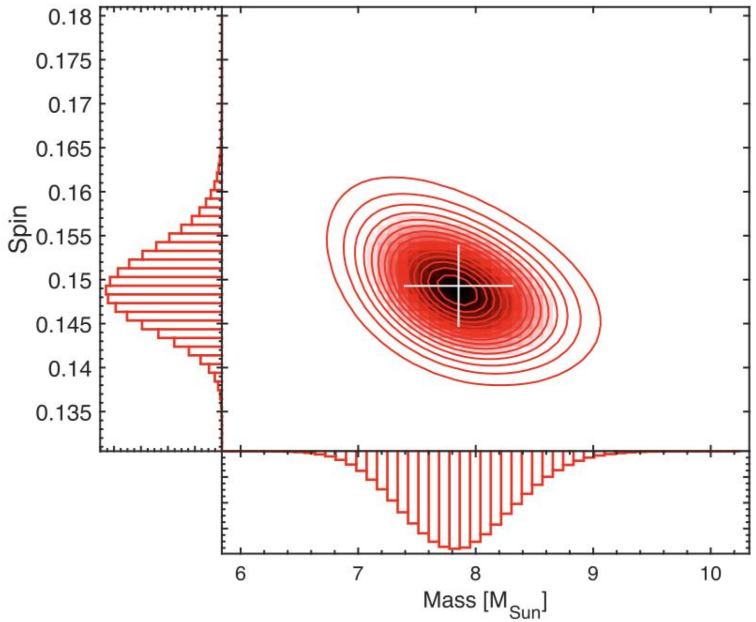
$$\nu_{nod} = \upsilon_\phi\left(1-\left(1+3a^2\left(\frac{M}{r}\right)^2\mp 4a\left(\frac{M}{r}\right)^{3/2}\right)^{1/2}\right)$$

Motta et al. 2014a,b

GR X-ray timing modelling

Latest result on XTE J1859+226





Motta et al. 1999

Values obtained so far:

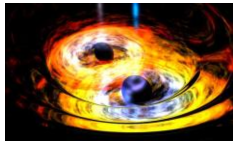
Source	Spin
GRO J1655-40	0.29 ± 0.01
XTE J1550-564	0.34 ± 0.01
MAXI J1820+070	0.799 ± 0.016
XTE J1859+226	0.149 ± 0.005

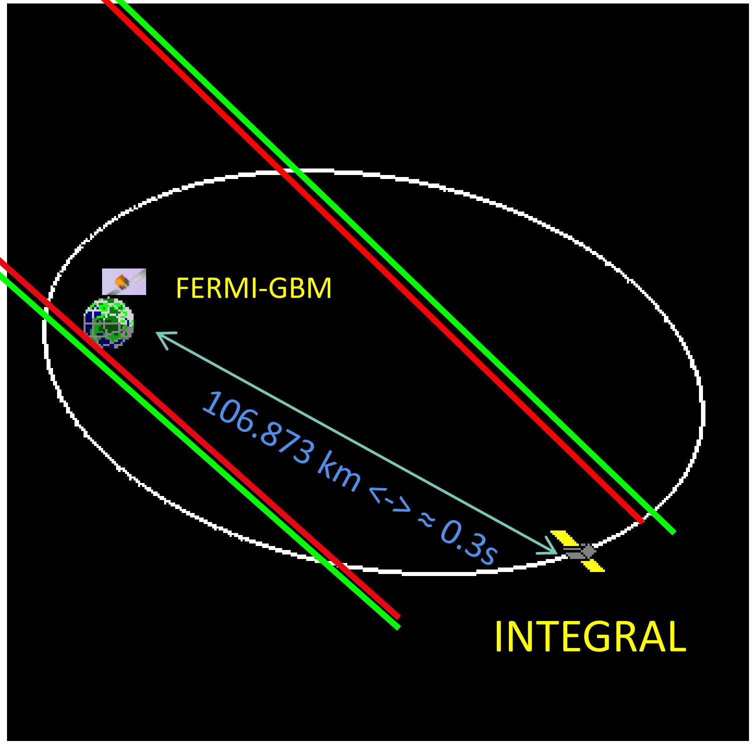
Direct way to obtain
mass and spin of black hole

INTEGRAL

Search for GW counterpart: the GW170817 case

Gravitational and electromagnetic signals
from two coalescing NSs





Arrival sequence of signals:

- Virgo (Pisa)
- FERMI LEO
- Geo Centre
- LIGO Livingston
- LIGO Hartford
- INTEGRAL HEO

INTEGRAL
Search for GW counterpart: the GW170817 case

Fundamental consequences

This is the **first multimessenger detection, with total of 5.3 sigma GW-GRB association significance**

At least some **short GRBs are associated to BNS mergers**

The 2 s delay comparing to 130 Mly distance implies that **speed of gravity** can be constrained to unprecedented precision:

$$-3 \times 10^{-15} \leq \frac{\Delta v}{v_{\mathrm{EM}}} \leq +7 \times 10^{-16}$$

Such a consistency between GW speed and speed of light, implies stringent **limits on Lorentz Invariance Violation**

This observation provides the **new insights into the EoS of the neutron matter**

LVC+Fermi+INTEGRAL 2017 10

INTEGRAL GW Team members:

A. Bazzano, E. Bozzo, S. Brandt, J. Chenevez, T. J.-L. Courvoisier, R. Diehl, A. Domingo, **C. Ferrigno**, L. Hanlon, E. Kuulkers, E. Jourdain, A. von Kienlin, P. Laurent, F. Lebrun, A. Lutovinov, A. Martin-Carrillo, **S. Mereghetti, L. Natalucci, J. Rodi,** J.-P. Roques, V. Savchenko, R. Sunyaev, **and P. Ubertini**, Et al.…

eXTP
Fundamental physics objectives

eXTP will study the **extreme of physics**: understanding the behavior of matter and light under **extreme conditions of density, gravity and magnetism. Physics of bright sources BH, NS, magnetars**

Dense Matter: which is the state of matter at supranuclear densities (i.e., in the neutron star's interior)?
Exotic states of matter? Quark stars?
Watts+2019

Strong Gravity: what are the properties of space-time under extreme gravity (i.e., in the vicinity of NS and BH)? Any deviations from Einstein's General Relativity theory?
De Rosa+2019

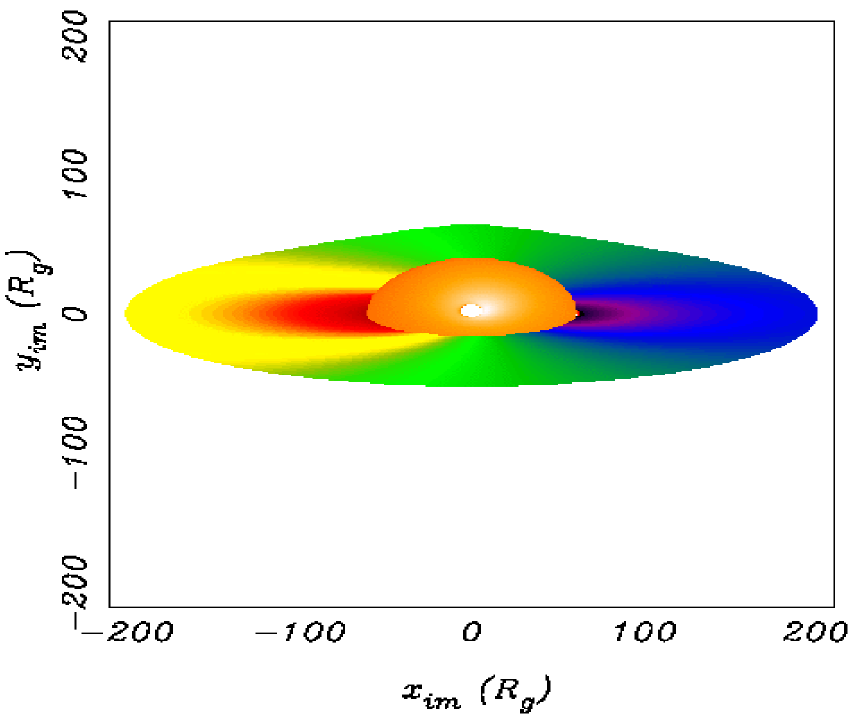
Strong Magnetism: which is the behavior of light in the presence of ultra-strong magnetic fields (e.g., in magnetars)? Are the predictions of the QED theory verified?
Santangelo+2019

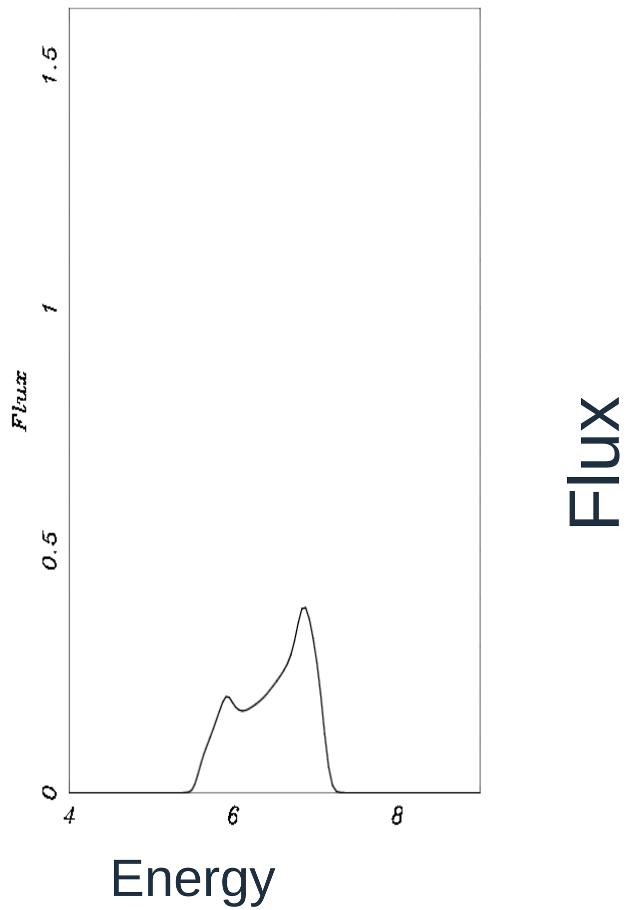
Science White papers: https://link.springer.com/journal/11433/volumes-and-issues/62-2

eXTP

Test case study: frame dragging in XRBs fast Fe line variability

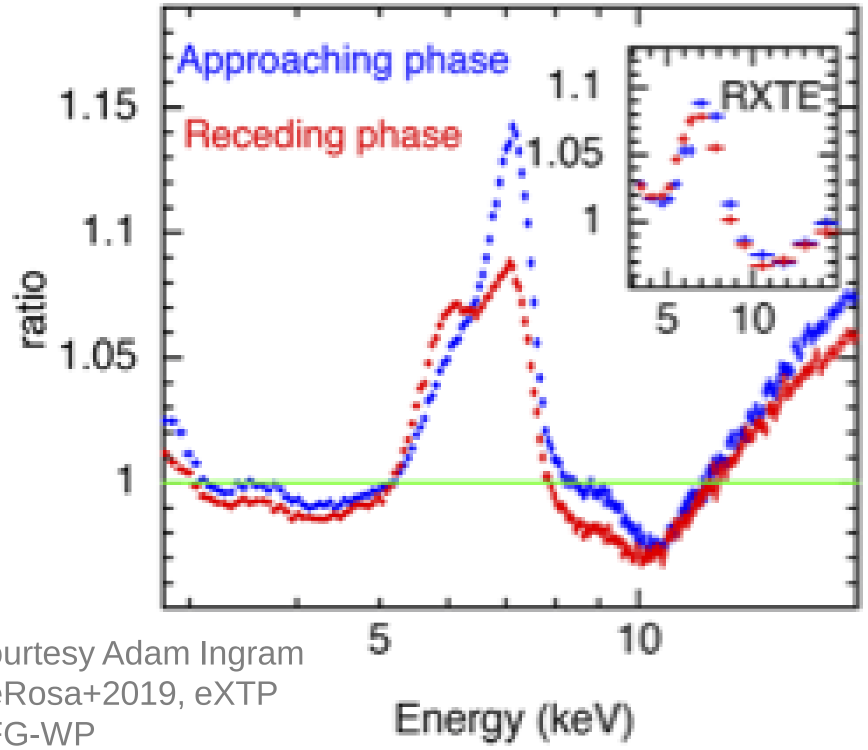
Ingram & Done (2012)



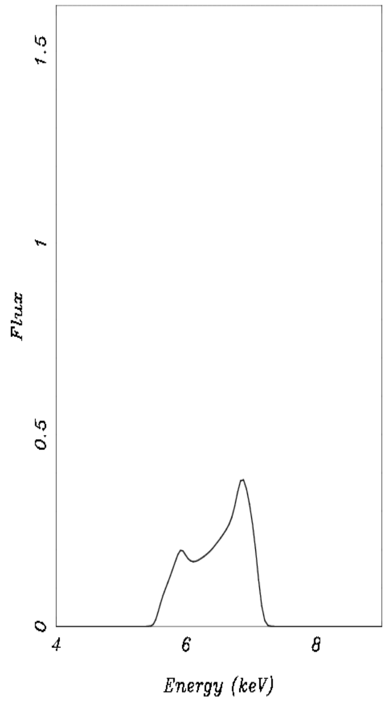


Frame dragging: central hot torus precesses
Reflection line profile varies periodically
Hard radiation illuminates the disc

eXTP
QPO phase resolved spectroscopy



Courtesy Adam Ingram
DeRosa+2019, eXTP SFG-WP



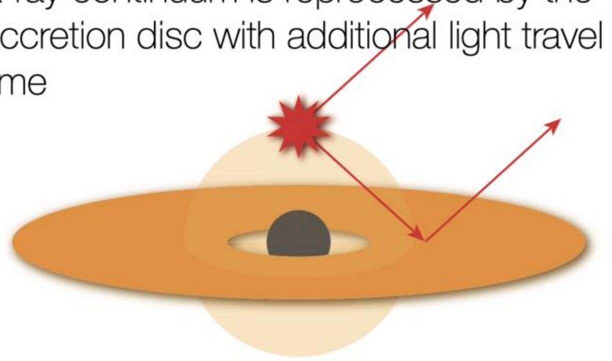
The very high count rate detected by the SFA+LAD allow to measure the **change in shape of the Fe line** (powerful diagnostic of accretion!) as a function of QPO phase resulting from **Lense-Thirring precession of the inner flow** —> inner flows geometry

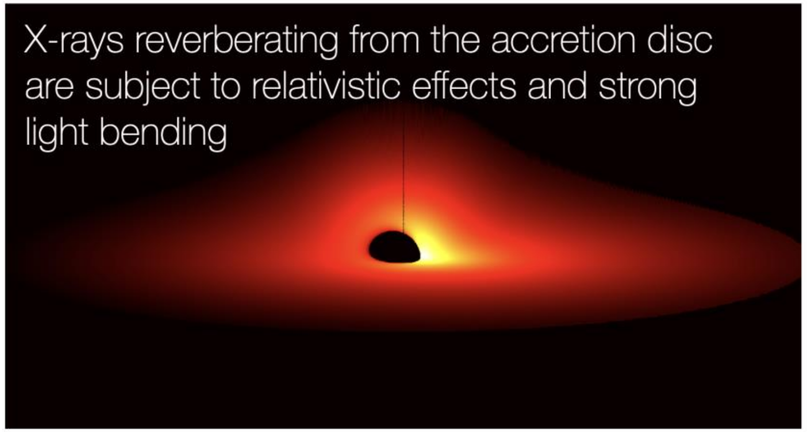
Athena

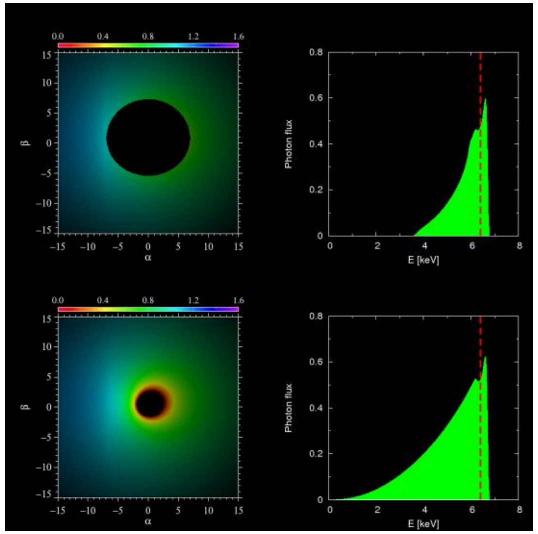
GR in strong field around a massive BH

Reflection (iron K line) from accretion disk around BH: **spin measurement**

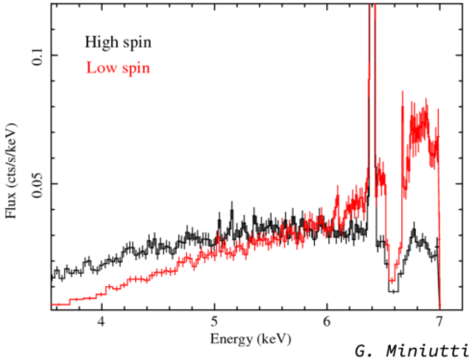
X-ray continuum is reprocessed by the accretion disc with additional light travel time







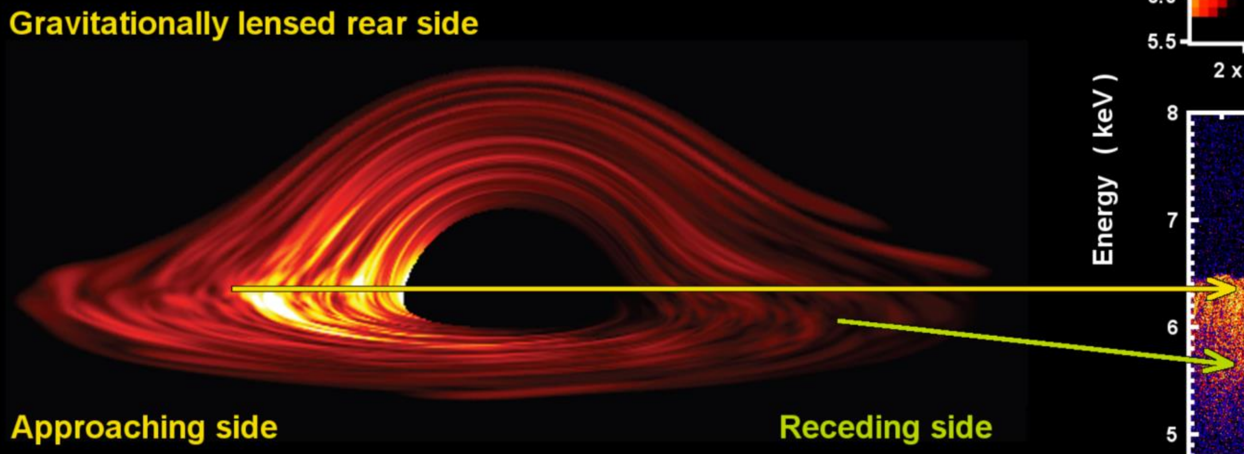
Simulated Athena/X-IFU **150 ks** Fe line profile for a low and high spins (a = 0, 0.998)

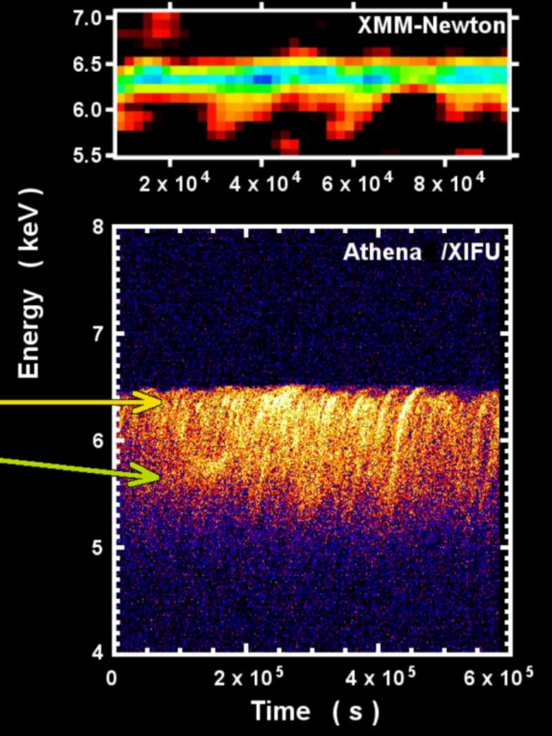


G. Miniutti

Athena
Mapping the accretion disk around Kerr BH

Snapshot from a time-dependent MHD simulation
of an accretion disk around a BH
(Armitage & Reynolds 2003)





- rings and hotspots of emission are seen due to turbulence, the emission from which should be modulated on the orbital timescale
- the first hints of this behaviour seen in XMM-Newton data (Iwasawa et al 2004, upper panel)
- the simulation with Athena/X-IFU (the lower panel) with BH mass of $3x10^7$ M_{sun}, 2-10 keV flux of $5x10^{-11}$ cgs, inclination of 20°

Athena

Testing deviations from GR

- The disc "MHD arcs" and disc reflection may be used as a **probe and test of General Relativity in the strong field limit** comparing the observations with the predictions of different gravity theories (Balbi et al 2021) ➔ in the so-called pseudo-complex theory the **line emission from an orbiting spot** should have different **timing and spectral characteristics** due to the different values of **the gravitational redshift** and **Keplerian frequency** (Boller & Müller 2013)
- ➔ Subtle differences in the line profile are also expected if the **no-hair theorem** is violated (Johannsen & Psaltis 2012)
- These kinds of measurements will certainly be very challenging, and their feasibility still needs to be fully addressed, their potential importance is large, especially for rapidly rotating black holes where relatively tight constraints on **potential deviations from the Kerr metric** are expected

Graphjc (Gravitational Physics Joint Center)

Iniziativa della Scuola Normale Superiore (SNS) e dell'INAF per unire competenze e iniziative dedicate alla ricerca e alla formazione sui temi della Fisica Gravitazionale

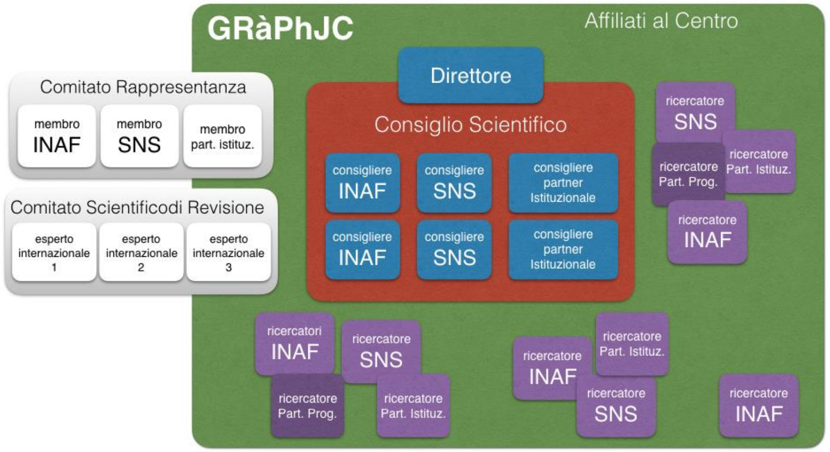
Fisica Gravitazionale: ✧ struttura a larga scala dell'Universo ✧ Cosmologia ✧ studio di oggetti compatti ✧ rivelazione di onde gravitazionali ✧ Astronomia multi-messaggero ✧ Studi sulla Relatività Generale.

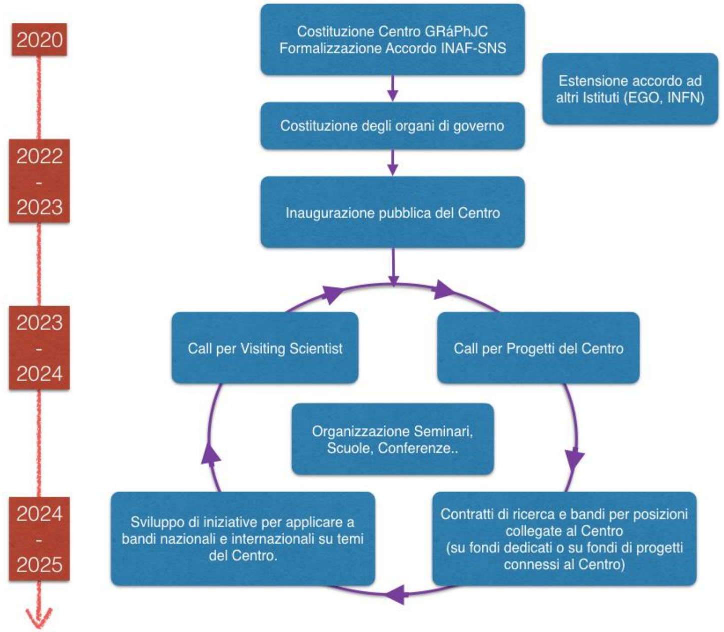
Obiettivi

- ospita e promuove progetti di ricerca di alto contenuto innovativo focalizzati alla Fisica Gravitazionale
- coadiuva l'incontro e la collaborazione tra studiosi italiani e stranieri, al fine di realizzare progetti di ricerca nelle rilevanti aree di investigazione
- promuove le attività di collaborazione, la sinergia e la coesione della comunità scientifica locale, e il coinvolgimento in programmi e progetti di ricerca nazionali internazionali
- sostiene la formazione di giovani scienziati sui temi del Centro attraverso il sostegno ai corsi di specializzazione e dottorato, scuole, workshop.

State of art

- Accordo sottoscritto da INAF e SNS
  - Interesse da parte di EGO
- Statuto del Centro approvato
- Spazi definiti presso complesso "Polvani" SNS
- Attività non ancora iniziate (COVID, rallentamenti struttura, …)
- Scheda INAF senza richiesta di grants





Registry

	People	Schede INAF
IAPS Experimental Gravitation	15	6
IRA VLBI	14	1
OATo Relativistic astrometry	22	4
OACa Pulsar Group	6	4
IRA EHT	7	1
GR X-ray timing modelling	3	3
INTEGRAL	7	6
eXTP	3	2
ATHENA	207	4
GRAPHJC	33	1

Discussion

Synergies: with all the other RSNs!

Message to audience: study of (relativistic) gravitation important both *per se* and as a fundamental tool to understand astrophysical phenomena

Question to audience: what is the role of fundamental physics in RSN4 and in INAF as a whole?

INAF
ISTITUTO NAZIONALE DI ASTROFISICA

IAPS ISTITUTO DI ASTROFISICA E PLANETOLOGIA SPAZIALI

Thanks for your attention!